# Surficial Geology, Geomorphology, and Erosion of Archeologic Sites along the Colorado River, Eastern Grand Canyon, Grand Canyon National Park, Arizona

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The eastern Grand Canyon in the vicinity of Cardenas Creek, Palisades of the Desert and Commanche Point on the skyline. Deposits of late-Holocene age occur in the vegetated area in the mid-ground on both sides of the river. Pleistocene-age gravel deposits form the steep, elevated banks adjacent to the river. Most of the archeologic remains are near the river and associated with the late-Holocene deposits .

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# Surficial Geology, Geomorphology, and Erosion of Archeologic Sites, along the Colorado River, Eastern Grand Canyon, Grand Canyon National Park, Arizona

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## Abstract

The average number of archeologic sites along the Colorado River in eastern Grand Canyon between River Miles 65-72 exceeds 12 $km^{-1}$; the largest concentration from Glen Canyon Dam to the mouth of Grand Canyon. The sites are mostly of Anasazi affiliation, dating from the Pueblo I to Pueblo II periods (A.D. 800-1200), although older sites of Basketmaker II affinity (about 200 B.C. to A.D. 400) and younger sites of Native American and Anglo affiliation are also present. All of the sites are closely associated with late-Holocene alluvial, debris-flow, and eolian deposits that accumulated in the river corridor during the past 2,500 years. The majority of sites occur on or beneath the surface of ancient alluvial deposits of the Colorado River, which form distinctive high terraces. Lateral shifts of the river extensively eroded these deposits and associated archeologic sites twice in prehistoric times, between A.D.300-700 and between A.D. 1200-1400.

In late historic times, numerous sites have been damaged or destroyed by erosion, which has accelerated since 1965-73. The daily operation of Glen Canyon Dam probably did not cause accelerated erosion in eastern Grand Canyon, although the presence of the dam indirectly effects erosion. Generally, sites are eroded by arroyo cutting in the short, ephemeral streams that drain the terraces of the river corridor. These streams are small; 90 percent have catchment area less than 20,000-30,000 $m^2$ and channel length of less than 300-400 m. Driven by excessive rainfall, arroyo cutting deepens, widens, and expands the channel system. The extent of arroyo cutting is related to past and present depositional levels of the river, which are local baselevels of erosion. The post-dam level is 3-4 m below the lowest pre-dam level; this decrease resulted from elimination of the annual flood and a six-fold reduction of sediment load. Eighty percent of tributary streams end above or on the post-dam depositional level, but during large runoff the channels are free to extend upslope as well as downslope toward the river. These channels will eventually extend downslope to the river, where the channel gradient will be lowered 3-4 m. Arroyo cutting will be intensified until channel gradients adjust to the post-dam baselevel.

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## Introduction

This study addresses erosion of Colorado River terraces in eastern Grand Canyon National Park (fig. 1). The history and causes of erosion during the past 2,500 years were inferred from studies of surficial geology and geomorphology. These studies were undertaken to determine if regulated streamflow, which began in 1963 with closure of Glen Canyon Dam, causes the ongoing erosion of terraces and associated archeologic remains. The work was part of the Glen Canyon Environmental Studies in cooperation with the U.S. Bureau of Reclamation.

Regulated flows, defined here as the water and sediment discharge regimen of the Colorado River since 1963, are substantially reduced in sediment load, sediment concentration, duration of high flows, and peak-flow rates compared with the unregulated flows of the pre-dam era. The average annual sediment load during 1941-57 at Grand Canyon was 60,000 Gg $yr^{-1}$ (66 million tons $yr^{-1}$); this was reduced by sediment storage in Lake Powell to 6,000 Gg $yr^{-1}$ (11 million tons $yr^{-1}$). Likewise, sediment concentration for a given discharge has decreased 2-3 times (Andrews, 1991). Under present conditions, sediment in the river is derived almost entirely from the Little Colorado (fig. 1) and Paria Rivers.

Peak-flow rates and the duration of high flows were also reduced. Between 1922-62 flow rates larger than 1,800 $m^3 s^{-1}$ (63,570 $ft^3 s^{-1}$) occurred on average 18 days $yr^{-1}$ (Williams and Wolman, 1984, p. 10-11). Since closure of the dam, flows have been above this level for about 30 days total, all during the summer of 1983 (Hyatt, 1990). In the pre-dam era between 1922-58, the average annual flood at

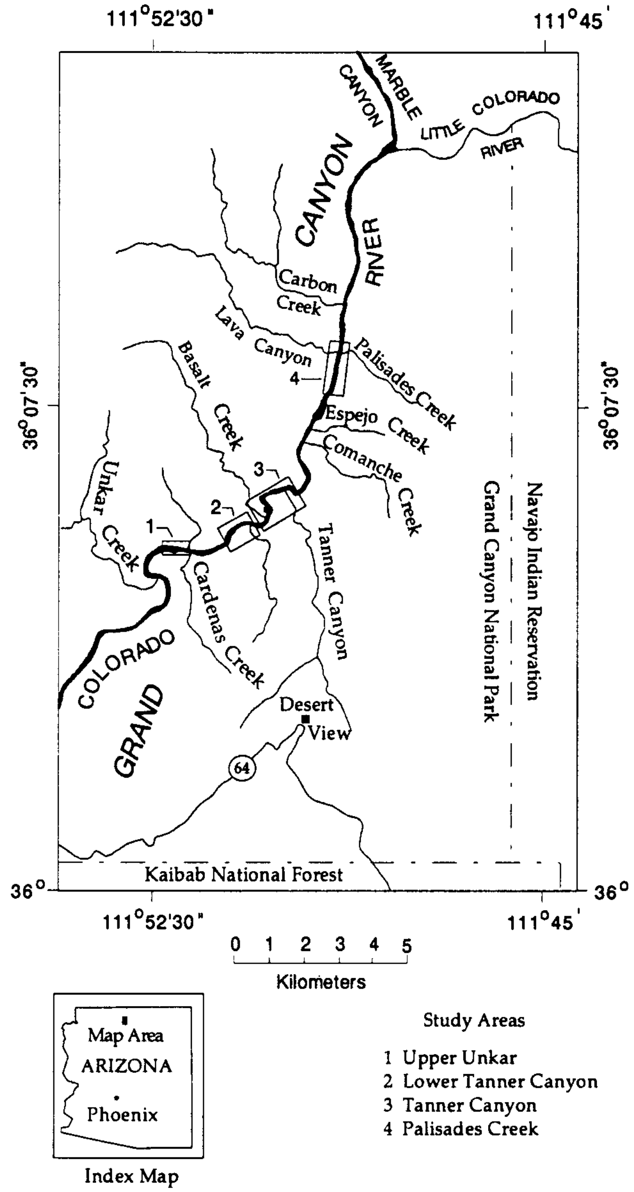



**Figure 1. The study area, eastern Grand Canyon, Grand Canyon National Park, Arizona.**

Lees Ferry was 2,400 $m^3\ s^{-1}$ (86,000 $ft^3\ s^{-1}$). The annual flood, which occurred in June and July, has a recorded maximum of 8,500 $m^3\ s^{-1}$ (300,000 $ft^3\ s^{-1}$) in July 1884, although flood-marks and other evidence suggest that a flood of 14,000 $m^3\ s^{-1}$ (500,000 $ft^3\ s^{-1}$) occurred in 1862. Other notable floods greater than 3,100 $m^3\ s^{-1}$ (110,000 $ft^3\ s^{-1}$) occurred in 1880, 1885-86, 1905-07, 1909 (twice), 1912, 1914, 1917, 1920-22, 1927 (twice), 1928-29, 1941, 1952, and 1957 (U.S. Bureau of Reclamation, 1990). In the post-dam era, the largest flood has been 2,700 $m^3\ s^{-1}$ (96,000 $ft^3\ s^{-1}$), and the average peak-flow rate has been only 980 $m^3\ s^{-1}$ (34,600 $ft^3\ s^{-1}$).

Changes of this magnitude are unprecedented in the past 2,500 years. Although peak-flow rates and duration of high flows could attain the post-dam levels during extended drought, sediment load and concentration almost surely could not decrease to present levels under natural conditions. The long-term sediment depletion has altered the erosional balance of the river corridor. One possible effect of this depletion is increased erosion by the streams that drain the terraces along the river. The erosional baselevel and gradient of these streams were maintained at a relatively high topographic level by sand deposited in the tributary channels during the annual flood of the pre-dam era; this depositional level is now substantially reduced.

Many archeologic remains in the river corridor were damaged or destroyed by erosion in the early 1980s (Jones, 1986; Fairley and others, 1991; J.R. Balsom and H.C. Fairley, 1989, personal communication). A number of the damaged sites are near or within the zone of regulated flows, suggesting that increased erosion was related to the daily operation of Glen Canyon Dam. Results of this study show that the operation of the dam has little direct influence on erosion in eastern Grand Canyon; rather, erosion is caused by rainfall in the river corridor. However, the presence of the dam with subsequent long-term reduction of sand concentration and peak-flow rates probably intensifies erosion.

## Methods

To understand erosion of the river corridor, we undertook geomorphic and surficial geologic studies at four areas in eastern Grand Canyon (fig. 1). Geologic studies are necessary to identify and map deposits with archeologic sites. This mapping process defines the spatial and temporal boundaries of the sedimentary phase of the site, which is the physical medium surrounding the archeologic remains (Waters, 1992, p. 15-16). In the river corridor, the sedimentary phase consists of several temporally bounded occupation levels; these levels occur on or within the deposits forming terraces, debris-flow fans, and sand dunes.

Although surface archeologic sites have been mapped (Fairley and others, 1991), the relation of the sites to the deposits has not been studied. Moreover, a substantial number of sites are present beneath the surface, judging from the abundant archeologic material exposed in the sides of small arroyos beneath the terraces. The extent of an archeologic site and the potential for additional sites, therefore, are determined by mapping the related deposits.

Specifically, the geologic studies consist of classification, dating, and mapping of the unconsolidated late Quaternary sedimentary deposits in the river corridor. Classification associates a deposit with the sedimentary process that formed it. The principal sedimentary processes of the river corridor are fluvial, colluvial, and eolian. Alluvium is deposited mainly by the Colorado River; colluvial deposits are typically debris flows originating in tributary streams (Webb and others, 1989); and the eolian deposits form active and inactive sand dunes. Archeologic sites are associated with each type of deposit. In some cases, the effect of these sedimentary processes is to erode and damage sites, whereas in other cases, sedimentation covers the site, protecting it from erosion.

Relative and absolute dating techniques were used to place the deposits in sequence and in time. The absolute age of the older deposits was determined from radiocarbon dates of organic material associated with the deposits. Wherever present, temporally diagnostic ceramics (potsherds) of Anasazi, Pai, Paiute, and Hopi affinity were also used for dating. Dates obtained from ceramic cross-dating vary by geographic region. The Pueblo II to Pueblo III transition varies only between A.D. 1150-1170, according to three published chronologies (Jones, 1986, p. 101). Ceramics associated with this transition date the end of alluviation of the deposit containing prehistoric archeologic material; thus, diagnostic ceramics provide tightly constrained absolute dates compared with radiocarbon.

Relative age, which places the deposits in sequence from oldest to youngest, was determined stratigraphically. The major stratigraphic units portrayed on maps consist of deposits representing distinct periods of erosion and subsequent deposition. These events and their corresponding stratigraphic relations are reflected in the terrace-like topography of the river corridor. The topography consists of a series of progressively higher terraces that become increasingly older as height above the river increases. This geomorphic expression of physical stratigraphy results from fluctuations of river baselevel, which lowers over time. Accordingly, deposits nearest the river with the lowest elevation are the youngest, whereas those farthest from the river with the greatest elevation are the oldest.

Geomorphic studies were undertaken to analyze the historic (post-1890) development of drainage patterns and their relation to erosion of the river corridor. The geomorphic evolution of the drainage system and historic erosion of archeologic sites were inferred from ground-based and low-altitude aerial photographs. Ground-based photographs taken in 1890, showing parts of the Lower Tanner Canyon, Tanner Canyon, and Palisades Creek study areas (fig. 1), were used to infer when the present drainage system began to develop. Sequential low-altitude aerial photography taken between 1965-84 was examined for evidence of erosional activity during the post-dam era.

Because rainfall and the resulting runoff are the principal causes of erosion in the river corridor, precipitation in the eastern Grand Canyon during the post-dam era was analyzed to search for the daily pattern and amount of rainfall associated with runoff. Daily rainfall records from four weather stations in the area were examined to characterize the rainfall of storms or stormy periods known to be associated with runoff and erosion in the eastern Grand Canyon. This information was used to identify periods with a high frequency of runoff-producing rainfall.

Finally, the principal geologic and geomorphic elements of the river corridor are too small to show on standard U.S. Geological Survey 1:24,000 scale topographic maps. For this reason, large-scale maps (Plates 1-4) were produced that range from 1:1,000 to 1:2,000 scale (1 mm on the map is 1 or 2 m on the ground, respectively) with contour intervals of 1 to 2 meters. These maps depict the topography of the river corridor at scales adequate to show drainage patterns and the surface expression of the deposits. The maps were produced photogrammetrically using a stereo analytical plotter mounted with low-altitude mapping aerial photographs. The small tributary streams shown on the maps were identified and plotted by the photogrammetrist. Ground surveys were done in 1989 and 1990 to rectify the aerial photographs; vertical control and latitude and longitude were obtained from maps and field measurements made by Lucchitta (1991).

## Cultural Resources of the Eastern Grand Canyon

The portion of the river corridor between River Miles 65-72 (between Palisades and Unkar Creeks in fig. 1) averages more than 12 archeologic sites $km^{-1}$. This is the largest concentration of sites along the river from Glen Canyon Dam to Separation Canyon, which is near the mouth of Grand Canyon. The sites range in age from about 200 B.C. up to the early 20th century; most sites are affiliated with the Pueblo II Anasazi, dating between A.D. 1000-1150.

The abundant Pueblo II Anasazi remains include masonry structures, granaries containing corn and squash, check dams, and other indications of a horticultural life-style, conclusive evidence that the eastern canyon was suitable for farming more than 800 years ago. Later and earlier occupants were more dependent on hunting and gathering than the Anasazi, exploiting the food resources of the canyon on a seasonal basis and extracting its mineral resources as circumstances allowed. The numerous camps, lithic scatters, and roasting pits left by these people provide a contrast with the architectural features of the typical Anasazi site.

The canyon has been and continues to be a spiritual resource for many cultures, as indicated by various shrines and rock-art sites scattered along the river corridor. The tangible record of all these human activities, and the changing focus of human endeavors in the canyon over time, are preserved in the archeologic sites of the Colorado River corridor. As these sites erode, their potential for contributing to understanding past human activities in Grand Canyon is irretrievably lost.

In the following discussion, a site is defined as one or more man-made features or clusters of artifacts representing a former locus of human activity. A feature is any deliberate human construction or modified area such as a hearth, check dam, rock-art symbol, hunting blind, granary, or habitation structure. Sites typically contain artifacts, which are either whole or fragmentary items such as potsherds, lithic debris, hammerstones, grinding slabs, glass bottles, tin cans, buttons, and basketry. Stylistic attributes of the prehistoric artifacts have been directly or indirectly dated by radiocarbon or dendrochronologic methods in other areas of the Southwest, thereby allowing archeologists to assign many of the cultural sites of Grand Canyon to specific temporal periods.

### Previous Archeologic Research

In 1953, the first archeologic inventory along the Colorado River in Grand Canyon was undertaken (Taylor, 1958). During this survey, sites were documented at the mouths of Nankoweap, Unkar, and Bright Angel creeks, opposite Deer Creek, and at South Canyon. From this limited evidence, Taylor (1958) concluded that there had been only sparse occupation of the inner canyon between A.D. 1000-1150 by Kayenta Anasazi populations from the North Rim.

Additional reconnaissance surveys in the early to mid-1960s indicated that this conclusion was premature (Jett, 1968). In 1961, Douglas W. Schwartz conducted a reconnaissance survey of the river corridor from Nankoweap to Unkar and reported 12 sites in this 32-km reach. Six of the sites recorded by Schwartz are in the present study area (fig. 1). These include a sherd scatter near the mouth of Lava Canyon, an architectural site downstream of Tanner Canyon, and a cluster of four rooms near the mouth of Basalt Canyon. In 1965, Euler and Taylor (1966) resurveyed the same section and reported additional sites, including several in the Upper Unkar area (fig.1), which is one focus of the present study.

The site in the Upper Unkar area, as noted by Euler and Taylor (1966, p. 39), "represents one of the largest prehistoric sites so far discovered in the inner gorge of Grand Canyon." Describing the site in some detail, they observed that "[c]lose to the river are several coursed masonry remnants and a heavy sherd concentration eroding from a sand bank." This area, later referred to as locality 1 by Jones (1986), was effected by extensive arroyo cutting in the summer of 1983, although the arroyos were weakly developed by at least 1980. A portion of locality 1 was illustrated by Euler and Taylor (1966), and that photograph is reproduced in a following section of the report as figure 8.

The early surveys were not intensive by present standards. Nonetheless, they revealed a canyon-wide Pueblo II settlement pattern characterized by small, dispersed habitations concentrated along arable portions of spring-fed tributaries, as well as sporadic use by contemporary Cohonina peoples and later by Southern Paiute, Hopi and ancestral Pai peoples (Euler and Taylor, 1966). Ceramics indicated that the Anasazi occupation spanned a 300-year period between A.D. 900-1200, with the period of greatest population density between A.D. 1050-1150. Evidence for earlier use of the canyon was exceedingly sparse and limited to a few occurrences of plain gray pottery, often associated with later materials. Evidence of a pre-ceramic occupation equivalent to the age of the late Archaic split-twig figurines (ca. 2500-1500 B.C.) was not found.

In the late 1960s, a multi-year excavation project at the mouth of Unkar Creek (fig. 1) produced the first detailed descriptions of Anasazi material culture and community organization in the Grand Canyon (Schwartz and others, 1980). These excavations also revealed an earlier Cohonina presence in the area, dating to about A.D. 900 (Schwartz and others, 1980, p. 9).

Additional excavations were not undertaken in the Grand Canyon until 1984, when the National Park Service initiated a stabilization project to protect five significant sites that were being eroded by arroyo cutting and visitation (Jones, 1986). One of the five sites included in this study was the large Anasazi complex of architectural remains in the Upper Unkar area (fig. 1). This site was included in the project at the last minute, because recent arroyo cutting had exposed and destabilized previously buried masonry structures and midden deposits. Emergency recovery measures were necessary to preserve information from this site before it was lost to erosion (Jones, 1986, p. 73).

The site in the Upper Unkar area is considered unusual, not only for its size and the presence of full-height masonry structures, but also because the ceramic assemblage suggested that occupation began in the Pueblo I period, which is poorly represented regionally. The occupation continued until about A.D. 1200, when most of the canyon was abandoned by the Anasazi (Jones, 1986, p. 52). Due to the large size of this site, only a small portion was excavated. Although a small number of Pueblo I ceramics were recovered during the excavations, the ceramic assemblage was dominated by later types. This fact and the relatively late radiocarbon dates from excavated structures indicated that the buried structures were associated with occupation dating between A.D. 1000-1200. Jones acknowledged the possibility of an earlier Pueblo I occupation at the site, based on the presence of Pueblo I sherds associated with slab-lined features in other portions of the site. However, she noted that "good stratigraphic contexts for the early occupation were not defined" at this site, nor at the other sites examined (Jones, 1986, p. 100-102).

A comprehensive archeologic survey of the entire river corridor was completed in the fall and winter of 1990-91 (Fairley and others, 1991). This survey recorded 475 prehistoric and historic sites between Glen Canyon Dam and Separation Canyon. Of the 475 sites recorded during the inventory, 238 are located on or in alluvium deposited by the Colorado River (Fairley and others, 1991). Fifty-two sites, constituting 11 percent of the inventory total, lie in the present study area (fig. 1), even though the area includes only 3 percent of the surveyed corridor. The sites include 62 occupational components (several sites were occupied more than once). Thirty components are related to the Anasazi, two components are of Cohonina ancestry, two of Hopi, one of Paiute, and nine are of historic Anglo affiliation. Three components included a mix of both Cohonina and Anasazi ceramics, while 15 lacked ceramics or historic artifacts. Three of the latter group were later assigned to the preceramic era based on radiometric determinations.

## Implications of Geoarchaeology Studies in the Eastern Grand Canyon

The information obtained from archeologic sites in conjunction with geomorphic research indicates that the highest alluvial terraces along the Colorado River in eastern Grand

Canyon were deposited during two aggradational episodes. The terrace deposits are termed the "striped alluvium" and the "pueblo alluvium;" they are discussed in a following section of the report. Numerous archeologic sites were buried during deposition of these alluviums. The abundant late Pueblo II Anasazi sites are contemporaneous with the latest aggradation. These sites, and later ones associated with Pai, Paiute, Hopi, and historic Anglo use of the Canyon, are readily visible on the high-sand terraces. Most evidence of earlier occupations, however, is buried under accumulated fluvial, colluvial, and cultural debris. The oldest occupation levels are recognized only where overlying deposits have been removed by erosion or by excavation.

The archeologic record along the river corridor is more complex than previous studies indicate. For example, although archeologists have known for several decades that Anasazi farmers made intensive use of the inner canyon during the Pueblo II period, the nature and extent of earlier occupations have long been a subject of debate; this is due mainly to the paucity of documented remains dating to the pre-Pueblo II period. The geoarcheologic studies show that there is a relative abundance of cultural remains pre-dating A.D. 1000, but they are typically buried 1-2 m below the surface. In most cases, exposures of these remains are limited to actively eroding arroyos of small ephemeral streams.

The geoarchaeology studies revealed an older buried occupation level near the base of the pueblo alluvium in the Upper Unkar area (fig. 1). This occupation level is associated with a pure assemblage of diagnostic Pueblo I ceramics. This deposit, which dates between A.D. 800-900 on the basis of ceramics, underlies a Pueblo II masonry structure which is buried by almost 2 m of colluvial and fluvial sediments, representing alternating river flood and slopewash deposition. The presence of the buried Pueblo I stratum is conclusive evidence of an occupation horizon predating the well-documented Pueblo II Anasazi occupation. Furthermore, the stratum demonstrates that surface archeologic remains are not necessarily representative of the entire range of archeologic resources present in the eastern Grand Canyon.

At the mouth of Lava Canyon (fig. 1), another series of buried cultural deposits were discovered, and the lowest occupation level is overlain by almost 2 m of sediment consisting of Colorado River alluvium interbedded with debris-flow material from the Lava Canyon drainage. The low elevation of a buried, slab-lined hearth relative to Pueblo II features present on a nearby terrace initially suggested that the lowest occupation level would predate the Pueblo I deposits at Furnace Flats; however, radiocarbon dates indicate a late Pueblo I or early Pueblo II age.

Subsurface sites in the Tanner Canyon area (fig. 1) have yielded the earliest cultural remains recorded in this part of Grand Canyon. In 1989 and 1990, several buried hearths were discovered eroding from fluvial sand deposits west of the mouth of Tanner Canyon. Radiocarbon dates of charcoal in two hearths at the base and top of the striped alluvium yielded calibrated dates (95 percent confidence interval) of 400-0 B.C. and A.D. 100-450, respectively. These dates, the lack of associated ceramics, and the abundance of associated bifacial thinning flakes are consistent with a Basketmaker II or terminal Archaic temporal assignment.

In addition to providing dating control for the alluvial deposits, these buried pre-ceramic sites provide information for exploring the little known period between the demise of the split-twig figurine makers and Pueblo period horticulturists. Currently, the cultural affiliation of this pre-ceramic occupation is unknown. Future studies of these buried sites could reveal whether the remains represent the first incursion of Anasazi horticulturists into the Grand Canyon or a separate cultural entity. This separate entity could have been the last vestige of the Archaic split-twig figurine makers or the initial representatives of the Cohonina culture.

The geoarchaeology studies in eastern Grand Canyon demonstrate that the alluvial deposits and associated archeologic remains reflect a complex flood history. Ongoing geoarcheologic studies in other portions of the river corridor suggest that the remnants of this complex flood history are preserved fragmentally along the length of the river. Due to differential preservation, the archeologic remains preserved in alluvial deposits in eastern Grand Canyon are not necessarily duplicated in other reaches of the river corridor. Thus, in one segment of the canyon, a sequence of deposits with the basal strata dating to the end of the late Archaic period is overlain by deposits on the surface dating to the Pueblo II period; whereas, in other sections, alluvium deposited after the Pueblo II period rests directly on bedrock. Because alluvial deposits are preserved differentially along the length of the river corridor, the type and age of sites present on the terraces vary accordingly.

This differential preservation has significant implications for interpretation of Grand Canyon prehistory. Archeologic studies that rely solely on traditional surface inventories for reconstructing the spatial distribution of prehistoric sites along the Colorado River are biased, and interpretations based on surface inventory data will be similarly skewed. For example, Fairley et al. (1991) found that Pueblo II remains are abundant in the eastern half of the canyon, whereas in the western portion (downstream of Kanab Creek) Pueblo II materials are sparse. Based on this spatial distribution, archeologists might hypothesize that the paucity of substantial Pueblo II remains in the western Grand Canyon results from an occupational hiatus, perhaps reflecting a cultural frontier zone separating the Pueblo II Anasazi in the eastern canyon from contemporary Cohonina or ancestral Pai. Although this hypothesis cannot be fully discounted, ongoing geoarcheologic work near Granite Park, 240 km downstream of the present study area, suggests an alternative explanation. The extensive burial of PII surfaces by younger deposits, rather than a regional absence, appears to be responsible for the limited Pueblo II remains in the western canyon.

## Generalized Upper Holocene Surficial Geology

The following sections discuss the prehistoric to modern deposits of the river corridor. This is necessary to understand where archeologic material occurs and how the material was eroded before the advent of regulated flows. The study suggests that significant erosion of deposits containing archeologic sites occurred in pre-dam times and was related to episodes of lateral-channel movement and instability lasting up to several centuries.

Classification and correlation of the late-Quaternary deposits of the river corridor are shown in figure 2. This figure shows the sedimentary and geomorphic classification of the deposits, the field terminology applied to them, and their age. In addition, the geologic and geomorphic relations of the alluvial deposits are shown schematically in figure 3. This figure is a composite developed from the relations at several areas.

### Geological Setting

A variety of bedrock units and surficial deposits with related geomorphic surfaces are present in the eastern Grand Canyon (fig. 1). The mapped deposits, except the older gravel deposits (units gvo and gvy of fig. 2), lie in the river corridor. Radiometric dating and archeologic remains indicate that the deposits exposed in the river corridor are late Holocene, which encompasses the past 2,500 years. The width of the corridor ranges between about 200 to 400 m, as measured from the lowest exposure of bedrock on either side of the river. Surficial deposits in eastern Grand Canyon are more widespread than elsewhere in the Canyon because the river corridor is relatively wide, which enhances sediment deposition and preservation.

Bedrock in and adjacent to the river corridor of the eastern Grand Canyon area is the Dox Formation and Cardenas Lavas (Huntoon and others, 1986), two of the thickest formations of the Early Proterozoic Unkar Group (Hendricks and Stevenson, 1990). The Dox Formation is fine-grained sandstone with interbedded shale and siltstone, all of distinctive reddish color. The Cardenas Lavas, a series of dark-colored basalt and basaltic andesite flows, are present locally in the river corridor. The lavas form dark, steep slopes and cliffs outside the corridor. Reworked clasts of the Dox and Cardenas formations occur in the surficial deposits of talus that form beneath steep slopes and in the alluvial and debris-flow deposits. The reworked Dox clasts impart a reddish color to the late-Holocene alluvial deposits.

Deposits of mostly consolidated gravel (units gvy and gvo of fig. 2) occur just outside of the corridor from near river level to more than 30 m above river level, as measured from the base of the gravel. The gravels are up to

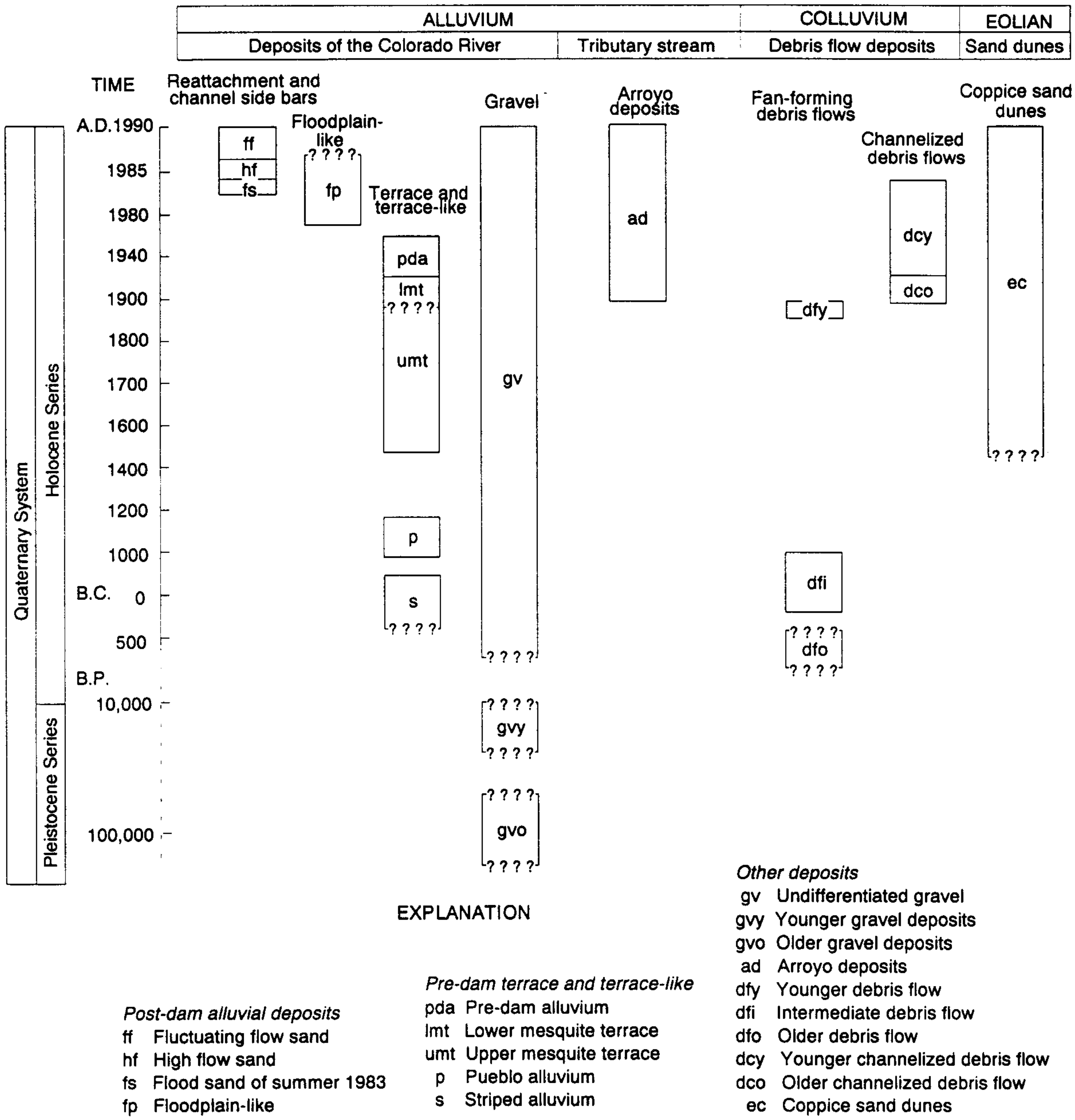



**Figure 2. Generalized classification and correlation of late Quaternary deposits. Question marks indicate uncertainty in age of deposits.**

30 m thick and consist of moderately-well rounded, boulder-size clasts of Paleozoic limestone and sandstone. Distinctive well-rounded clasts of porphyritic rock occur sparingly in the gravels. These clasts were carried by the river from distant sources in the laccolithic mountains of the Colorado Plateau.

The gravels are ancient, high level channel-fill deposits of the Colorado River dating from the Pleistocene. In many places, the contact between gravel and bedrock is strongly concave and the contact slopes steeply toward the river. This situation represents the margin of an ancient river channel. The Pleistocene age of the gravels is based on their topographic position above known Holocene deposits and by correlation with dated late-Pleistocene deposits elsewhere in eastern

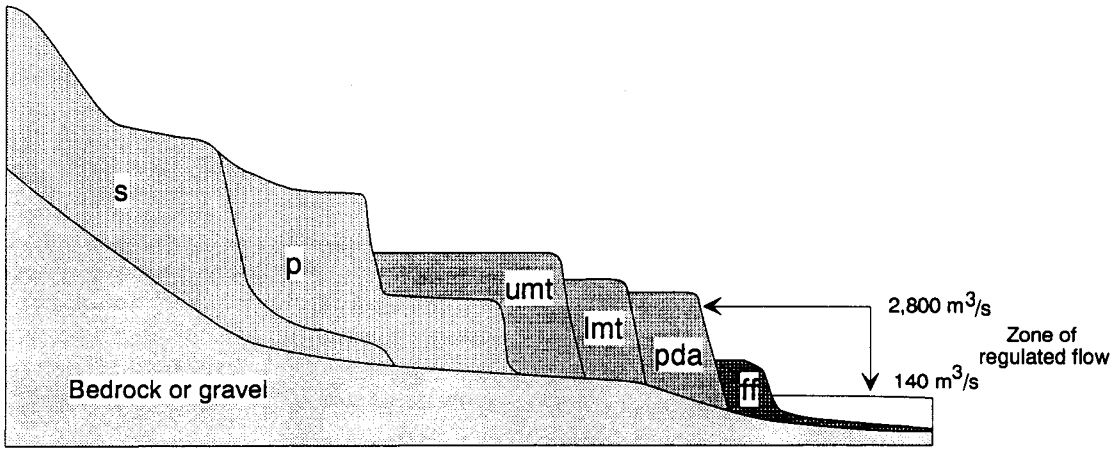



**Figure 3. Generalized cross-section showing geomorphic and geologic relations of alluvial deposits. Symbols explained in figure 2.**

Grand Canyon (Machette and Rosholt, 1991). The younger gravel (unit gvy) probably correlates with river levels one to three, and the older gravel (unit gvo) probably correlates with river levels four and five of Machette and Rosholt (1991). River levels one to three range in age from 5 ± 5 to 40 ± 24 ka years; river levels four and five range from 75 ± 15 to 150 ± 30 ka years.

This information suggests that the younger gravel (unit gvy) is probably older than about 10 and younger than 40 ka years, and the older gravel (unit gvo) is older than 75 and younger than 150 ka years. The younger gravel (unit gvy) is considered late Pleistocene, rather than late Pleistocene to Holocene, based on its coarser grain size (gravel compared with sand), much greater thickness (tens of meters compared with meters), and evidence of extensive bedrock erosion after deposition of the gravel that resulted in widening and realignment of the river corridor.

## Pre-dam Alluvium and Related Terraces

### *Striped and Pueblo Alluviums*

The prehistoric archeologic remains are associated primarily with the pueblo and striped alluviums (units p and s of fig. 2). The remains occur on or near the surface or buried within the deposits, where they are undetectable unless exposed by erosion. These deposits form the highest terrace of the river corridor and they are the oldest Colorado River deposits adjacent to the river (fig. 3).

The striped alluvium consists of light-colored sand interbedded with pebble to small-cobble gravel composed of red clasts of Dox Sandstone. These gravel beds impart the distinct "stripes" that are characteristic of the deposit. The gravel beds increase in number and thickness in the direction of the nearby bedrock hillslopes. The gravel resulted mainly from sheetwash, although minor deposition from hyperconcentrated streamflow and small debris flows is evident. The sand beds increase in number in the direction of the river. These beds are largely of fluvial origin; they contain relatively high quantities of silt and sand, and fluvial sedimentary structures are present locally, although the deposits typically lack sedimentary structures.

The pueblo alluvium derives its name from the locally abundant archeologic material of Pueblo II affinity, although diagnostic Pueblo I and early Pueblo III ceramic material is also present. The archeologic material consists of potsherds, flakes, rock alignments, upright slabs, walls, and other artifacts or features. This deposit consists mainly of poorly-sorted, very-fine grained sand of fluvial origin interbedded locally with moderately well-sorted fine-grained sand of possible eolian origin. Gravel beds forming red stripes are also present, but they are less well developed than those of the older striped alluvium. The pueblo alluvium disconformably overlies the striped alluvium in the Lower Tanner Canyon area (fig. 1). The contact between the alluviums is an eroded surface with up to 1 m of relief locally, and stratification in the striped alluvium is truncated beneath the contact. Thus, the pueblo alluvium is stratigraphically distinguishable from the striped alluvium, although there is little topographic separation between the alluviums at the surface.

*Upper and Lower Mesquite Terraces*

The mesquite terraces (units umt and lmt of fig. 2) are narrow, discontinuous, surfaces that are topographically below the striped and pueblo alluviums (fig. 3). These terraces lie in the "old high water zone" of previous studies (GCES, 1988, p. B-10; Johnson, 1991). The name stems from the abundant bushes and trees of western honey mesquite (*Prosopis glandulosa* var. torreyana; Turner and Karpiscak, 1980) present on the terraces.

At Palisades Creek (fig. 1), the upper mesquite terrace forms an extensive surface that overlies the pueblo alluvium (fig. 3), although the alluvium of the upper mesquite terrace is extensively reworked and partially covered by sand dunes. The upper and lower mesquite terraces are composed of material similar to the underlying alluviums; both are poorly sorted, very-fine grained, silty sand of Colorado River origin. The terraces are distinguished by their topographic positions relative to one another; the lower mesquite terrace is topographically below the upper terrace (fig. 3). They are further distinguished by the presence of mesquite trees that appear distinctly older on the upper terrace. At the Lower Tanner Canyon locality, a radiocarbon date of the pith and innermost rings of a senescent mesquite bush at the base of a coppice sand dune yielded a germination date of A.D. 1240-1340.

Photographs of the Palisades Creek area taken in January 1890 by Robert B. Stanton (Smith and Crampton, 1987, p. 149-159) were used to date the lower mesquite terrace and to interpret the relation between the upper and lower mesquite terraces. These photographs (R.H. Webb written communication, 1990, stake numbers 1439c and 1431b; Stanton photograph numbers 385 and 382) show the upper and lower mesquite terraces. The upper mesquite terrace in 1890 was vegetated and appears to not have been recently flooded. The lower mesquite terrace was only lightly vegetated with high-albedo deposits of sand and dark elongated objects interpreted as widely scattered driftwood. This suggests that the upper mesquite terrace was inactive by 1890, whereas the lower terrace had been recently flooded.

These terraces were formed during the larger floods of the protohistoric to historic period. Judging from its relatively high topographic position above the lower mesquite terrace, sand of the upper mesquite terrace probably accumulated during the largest floods of the post-Anasazi era. The lower mesquite terrace, which accommodated floods with lower stage than those effecting the upper terrace, was quite likely overtopped during the flood of record in July 1884 (estimated peak discharge of 8,500 $m^3 s^{-1}$). Driftwood that contains less than 5 percent of milled and cut wood occurs in the previously discussed area of high albedo in the Stanton photograph (R.H. Webb Stake Number 1439c). The paucity of milled or cut wood implies that the driftwood is historic and might have been deposited by the 1884 flood.

The alluvium of the lower and upper mesquite terraces is considerably thinner and occupies much less area than the pueblo alluvium and striped units. Generally, the limited thickness and extent of the deposits suggest that they probably do not represent significant, sustained deposition by the river. The tentative conclusion is that the river has been in quasi-equilibrium since erosion of the pueblo alluvium.

*Age of the Prehistoric to Protohistoric Deposits*

The age of the striped alluvium, pueblo alluvium, and alluvium of the upper mesquite terrace is constrained by radiocarbon dates and archeologic material. Organic material was collected from the three units and dated using the radiocarbon method. The units were mapped in the field using aerial photographs, and the units portrayed in this manner were then transferred photogrammetrically to the topographic base maps. In some cases, the stratigraphic position of the carbon sample in a particular unit is unknown, although field relations identify clearly the stratigraphic unit. The results of the dating are shown in figure 4, which shows the age range of 25 radiocarbon dates in calendar years arranged by mapped stratigraphic unit.

The dates are shown in calendar years for comparison with the archeologic chronology. Calibration of radiocarbon years to calendar

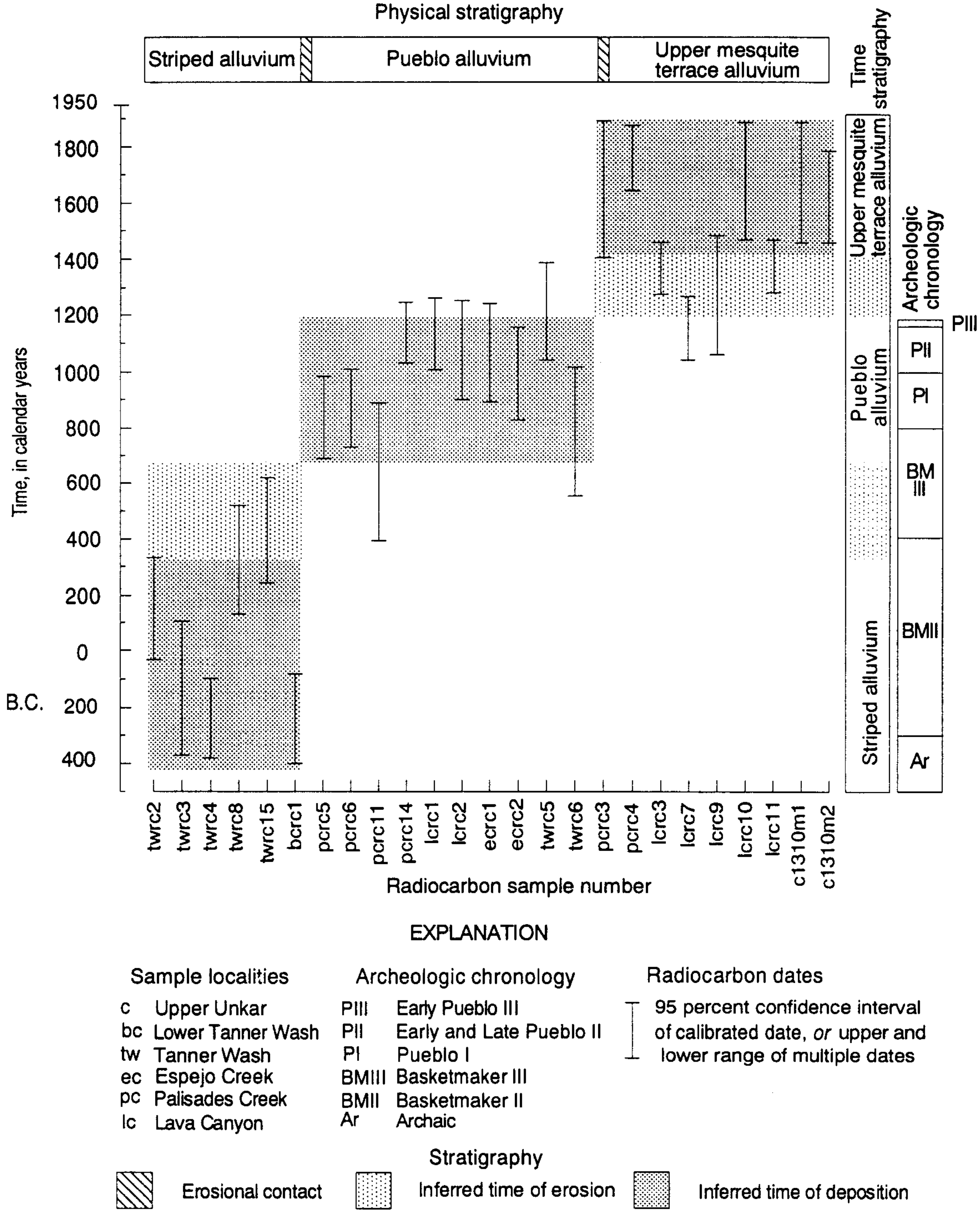



**Figure 4. Radiocarbon dates calibrated to calendar years arranged by stratigraphic unit showing relations among physical stratigraphy, time stratigraphy, and archeologic chronology.**

years was done with the Gronigen Radiocarbon Calibration Program (version of June 1991) furnished by the U.S. Geological Survey Radiocarbon Laboratory (Reston, Virginia) using data current through 1989. In this procedure, multiple dates are possible for a single sample because of secular $^{14}C$ fluctuations (Klein and others, 1982). The age range shown in figure 4 is the 95 percent confidence interval of the calibrated date; multiple dates are shown as a single range taken from the oldest to youngest of the multiple dates.

Figure 4 shows that several dates overlap between the striped and pueblo alluviums and between the pueblo alluvium and the alluvium of the upper mesquite terrace, but the physical stratigraphy demonstrates that the deposits are bounded by unconformities, which are periods of erosion and nondeposition. Secular variation of $^{14}C$, the inherent precision of $^{14}C$ measurements, and uncertainties regarding sample provenance (Taylor, 1987, p. 140) account for overlapping radiocarbon dates.

Deposition of the striped alluvium probably began before 400 B.C. and could have lasted until about A.D. 300 (fig. 4). This is consistent with the aceramic character of the archeologic remains in the alluvium. This indicates that the deposit predates the Pueblo era and is most likely of Basketmaker II age. Deposition of the pueblo alluvium probably began by about A.D. 700, which is supported by the presence of Pueblo I ceramics near the base of the alluvium in the Upper Unkar area (fig. 1) that date from A.D. 800-900. The period of erosion and nondeposition probably lasted about 400 years, from A.D. 300-700.

The lack of Anasazi ceramics and other materials in the upper mesquite terrace indicate that it post-dates the Anasazi occupation and is younger than about A.D. 1200. This interpretation is supported by the presence of late Pueblo II to early Pueblo III ceramics present near and on the surface of the pueblo alluvium. These ceramics suggest that the Anasazi abandoned the area between A.D. 1150-1200. Deposition of the alluvium forming the upper mesquite terrace must have begun after A.D. 1150-1200. The information in figure 4 suggests that deposition of the upper mesquite terrace alluvium could have begun as late as A.D. 1400. Thus, the period of erosion and nondeposition might have lasted 200 years, between A.D. 1200-1400.

### *Prehistoric Erosion of Archeologic Sites*

The two periods of prehistoric erosion and nondeposition discussed above show that erosion and removal of archeologic material has occurred in the recent geologic past. During the two erosional periods substantial quantities of alluvium and associated Basketmaker and Pueblo archeologic material were removed, judging from the discordant relation between the present channel and the terraces. The immediate cause of the erosion in each case was probably a major shift in channel position, both horizontally and vertically. In contrast, erosion during historic time resulted from the fluvial activity of short tributary streams that drain the surface of the older alluviums.

### *Pre-dam Alluvium*

The pre-dam alluvium and flood debris (pda of fig. 2) form a terrace, or in places a scoured surface, that is topographically beneath the lower mesquite terrace (fig. 3). The dominant vegetation at this level is saltcedar (*Tamarix chinensis* Lour.; Turner and Karpiscak, 1980). These trees are typically large, mature, and partially buried in the alluvium. Dates obtained from two trees at the Palisades Creek area (fig. 1) indicate germination in 1937 and 1951. Flood debris contains numerous artifacts dating from the mid-1930s to mid-1950s, and the driftwood is dominated by milled and cut wood. This terrace and related deposits formed during the larger floods of the 1930s to 1957. These floods were as large or most likely larger than the mean annual flood, which on average occurs about every 2.3 years (Dalrymple, 1960).

The terraces reflect a long-term pattern of declining flood magnitude. The pattern begins with an early period of large floods (upper mesquite terrace), followed by a period of somewhat smaller floods (lower mesquite terrace), and culminating with the relatively small floods of the lowest pre-dam terrace. This apparent decline of flood magnitude over the past 600 years is not comparable to the changes since closure of Glen Canyon Dam, as large quantities of sediment were still present in the system.

### *Undifferentiated Gravel Deposits*

Finally, gravel deposits (unit gv of fig. 2) with exposed thickness of 4-5 m are widespread in the river corridor. The deposits are unconsolidated, have a coarse-sand matrix, and clasts are cobble to boulder size. The clasts are rounded to subrounded and composed of local Paleozoic and Proterozoic formations. The gravel deposits are the substrate for the sand-size Colorado River alluvial deposits (fig. 2). Because of the relatively large size of the gravel clasts, they are immobile under most flow conditions of the Colorado River (except conditions in the rapids) and tributary streams. Thus, the gravel deposits control the position of the river and in places limit downcutting of the tributary streams.

## Post-dam Alluvium

Post-dam alluvium of the Colorado River consists mainly of channel side bars and floodplain deposits (units fs, hf, ff, and fp, respectively, of fig. 2), which are referred to as beaches by river runners. Schmidt and Graf (1990) refer to the post-dam alluvium in the study area as channel margin deposits, which typically form in zones of recirculating flow. Generally, channel side bars are deposited in low velocity areas adjacent to the river, where they form narrow strips of sand at three topographic levels. In places, channel side bars are further divided into reattachment bars, which form relatively broad expanses of sand.

Reattachment bars result from recirculating flow that develops in the distinctive, arcuate topographic setting downstream of a large channel constriction, which is usually a debris-flow fan. Downstream of the constriction, the flow separates from the main current and moves upstream, rejoining the main current at the head of the recirculation zone (Schmidt, 1990). At the Palisades Creek area and elsewhere in Grand Canyon, reattachment bars have been the subject of several studies that addressed the sedimentology and relation of the deposits to regulated flows (Schmidt, 1990; Schmidt and Graf, 1990; Rubin and others, 1990).

From the perspective of the present study, the post-dam alluvial deposits record the depositional activity of the Colorado River since 1983. Deposits dating from 1963-83 are not present, except for floodplain-like deposits (unit fp of fig. 2) at the mouth of Lava Canyon and east of Basalt Creek (fig. 1). This lack of post-dam deposits before 1983 suggests that either very little deposition occurred during 1963-83 or that the deposits were eroded during the floods and prolonged high releases of 1983-86.

Sand deposited during the 1983 flood (unit fs of fig. 2) is distinctively light colored, well sorted, and very-fine grained with silt and clay content less than 5 percent. The sand is typically about 1 m thick and its distribution is spotty; where the sand is absent a flood line showing evidence of scour is typically present. The scour line is marked by an alignment of relatively small, submature saltcedar that germinated between 1970-83. This sand and related floodmarks are topographically beneath the pre-dam alluvium, suggesting that the depositional level of the 1983 flood was below the depositional level of the pre-dam era.

At the Upper Unkar area (fig. 1), however, the 1983 flood-scour line is above the base of the pueblo alluvium, where an archeologic feature (Feature 10 on Plate 1) was eroded. This is the only location in eastern Grand Canyon where the 1983 flood was in contact with the pueblo alluvium. The configuration of the channel at this locality probably enhances erosion of the pueblo alluvium at moderate flood levels such as the 1983 flood (2,700 $m^3 s^{-1}$; 96,000 $ft^3 s^{-1}$). The Upper Unkar sites are located on the outside of a bend in the river formed by a large gravel bar (Plate 1). During moderately high floods when the island is overtopped, water level is raised above the base of the pueblo alluvium. For a given discharge at this locality, the high elevation and large area of the island increases flood stage relative to the pueblo terrace.

The high-flow sand (unit hf in fig. 2) is a very-fine to fine-grained sand with silt and clay content greater than 5 percent. It is distinguished from the 1983 flood sand by having a lower topographic position. The high-flow sand was deposited primarily during the high flows of 1984-86. The fluctuating flow sand (unit ff of figs. 2 and 3) resembles the high-flow sand except that it has a lower topographic position and it is distinctly stratified (Rubin and others, 1990).

The deposits of the post-dam floodplain are present immediately upstream of Lava Canyon and east of Basalt Creek in the Tanner Canyon area (fig. 1). At Lava Canyon, this alluvium is fine-grained sand that is about 1 m thick. The floodplain is heavily covered with saltcedar and arrowweed (*Pluchea sericea*; Turner and Karpiscak, 1980). A date from saltcedar rooted at the base of the floodplain alluvium indicates that the sand was deposited since 1970.

A broad pattern of erosion followed by deposition at progressively lower levels was repeated three times beginning in 1983, resulting in the three topographic levels of channel side bars. The largest flows of the post-dam era were in June-August of 1983 (Hyatt, 1990), when peak discharge was 2,700 $m^3 s^{-1}$ (96,000 $ft^3 s^{-1}$) and sustained flows were above 1,400 $m^3 s^{-1}$ (50,000 $ft^3 s^{-1}$). During May-June of 1984-86, sustained daily releases were the second highest of the post-dam era ranging from about 900 to 1,400 $m^3 s^{-1}$ (32,000-50,000 $ft^3 s^{-1}$). After 1986 through October 1989, seasonal variation was largely eliminated and flows fluctuated up to a daily maximum of about 900 $m^3 s^{-1}$ (32,000 $ft^3 s^{-1}$). Declining seasonal flow rates resulted first in partial erosion of the earlier formed sand bar followed by deposition of sand at the level of the prevailing flow regimen.

Recent events have altered the fluctuating flow sand, as the sand is no longer present at the surface. A flood on the Little Colorado River (fig. 1) resulting from unusual rainfall over northern Arizona in winter 1993 peaked on January 12-13 at the Phantom Ranch gage at 976 $m^3 s^{-1}$ (34,500 $ft^3 s^{-1}$) with a sediment load of about 0.9 Gg (preliminary estimates of Andrews, 1993, personal communication). The flood was not particularly large, having a recurrence interval of about 10 years. Nonetheless, sediment was deposited on the fluctuating flow sand up to the level of the high flow sand throughout the study area (fig. 1). Deposition of 1-2 m of sediment in the zone of fluctuating flow was observed as far downstream as Diamond Creek in western Grand Canyon.

## Tributary Stream Deposits

The tributary stream alluvial deposits (unit ad of fig. 2) consist of sand and pebble to small-cobble gravel. These deposits are present mainly in the larger arroyos of tributary streams; they are derived from hillslope erosion of bedrock and from erosion of older alluvial deposits. The deposits result partly from historic erosion of the striped and pueblo alluviums. Generally, the stream deposits date from the late 1970s to the mid-1980s, a period of unusually heavy rainfall and runoff in eastern Grand Canyon.

## Colluvium

Debris flows, which are slurries of sediment and water having less than 40 percent water by volume (Webb and others, 1989), form the principal colluvial deposits of the river corridor, although talus is present at the base of steep slopes. Ancient debris-flow deposits are important archeologically, because they were the substrate utilized by the Anasazi for construction. In protohistoric time, fire hearths and other rudimentary structures were constructed on the debris-flow surfaces.

Debris flows, in addition, affect erosion of the pueblo and striped alluvium. In places, younger debris-flow deposits have covered the alluviums, protecting them from subsequent erosion. The flows are locally erosive, however, and are associated with dissection of the archeologic alluviums. Equally important, the present course of the Colorado River, areas of sand deposition, and the location of rapids are largely controlled by the presence of ancient debris-flow deposits.

Debris-flow deposits of the eastern Grand Canyon occur at two spatial and temporal scales. Fan-forming debris flows (units dfo, dfi, and dfy of fig. 2) are the largest and oldest, and form the surface and subsurface of large debris-flow fans such as Palisades Creek, Tanner Canyon, and Basalt Creek (fig. 1). In contrast, channelized-debris flows (units dcy and dco of fig. 2) are substantially smaller and younger, and they are confined to the deeply entrenched channels that cross the fans. The deposits of the debris flows are broadly similar, consisting primarily of a clast-supported matrix of angular to subangular gravel ranging in size from granules to boulders over 3 m on an edge. The matrix is a poorly sorted mixture of clay to coarse sand or granule gravel. Webb and others (1988, 1989) discuss the composition, mechanical properties, and frequency of debris flows, and the effects of channelized-debris flows on rapids.

The fan-forming debris-flow deposits (fig. 2) are well developed at Palisades Creek. Three deposits or their eroded remnants are present on the surface of the Palisades Creek fan. The stratigraphic relations of the debris-flow deposits are exposed on the south side of Palisades Creek, where four debris-flow gravels ranging in thickness from 0.4 to 1.2 m are interbedded with four gravel beds of fluvial origin. Debris-flow deposits of similar age and areal extent are also present at the other locations.

On the surface of the fan, the deposts are distinguished by the degree of weathering of detrital clasts. The older debris-flow unit consists of the two basal debris-flow gravel beds exposed along Palisades Creek. This unit has clasts that are dark with desert varnish and exhibit tafone weathering, which imparts a distinctive cavernous or honeycomb structure to the clasts. The intermediate-age debris flow lacks tafone and has less densely developed desert varnish. The surface of limestone clasts are pitted by weathering processes, and the older and intermediate surfaces have characteristic pit depths. Weathering pits on clasts of the older debris flow range in average depth from 3.9 to 6.2 mm; pit depths on the intermediate flow range from 1.4 to 3.4 mm. Clasts on the surface of the younger debris flow lack desert varnish, and the clasts are fresh appearing without pitting.

The three flows are dated by historic photographs, radiocarbon, and by their relation to dated archeologic structures. The youngest debris flow is present in a Stanton photograph (R.H. Webb Stake Number 1439c) of the Palisades debris-flow fan. In 1890, the surface of the youngest debris flow was fresh appearing, similar to its present condition. At the distal end of the fan, the debris flow is only about 20 cm thick and consists of a clay and silt matrix with pebble-size clasts. The greatly thinned debris flow overlies driftwood deposited with sand of the upper mesquite terrace. The outermost rings of this driftwood were radiometrically dated at A.D. 1840-1890.

The intermediate-age flow is also present at the distal end of the debris fan, where it is only about 20-30 cm thick and consists mainly of matrix-supported pebbles and small cobbles. The surface of the flow was utilized by the Anasazi, as indicated by the walls of an early-Pueblo II structure built about A.D. 950 that penetrate the debris-flow gravel. This intermediate-age debris flow pre-dates A.D. 950. The age of the older debris-flow unit is presently unknown, but the increased pit depths and tafone weathering suggest that it is probably 500-1,000 years older than the intermediate-age flow.

The Stanton photograph (R.H. Webb Stake Number 1439c) shows that Palisades Creek was deeply entrenched, and debris flows since at least 1890 have been confined to this channel. Debris-flow levees in the channel indicate that at least two flows have occurred since 1890. These channelized-debris flows (fig. 2) did not overtop the debris-flow channel. However, the flows deposited a relatively small fan at Lava Canyon Rapids (Plate 4).

The fan-forming debris flows are larger and occur less frequently than the smaller, channelized flows studied by Webb and others (1989). Nevertheless, the smaller debris flows had major effects on the hydraulics of the Colorado River (Webb and others, 1988). The effect of a debris flow the size of those forming the Palisades Creek fan could be catastrophic and might easily render a rapid unnavigable.

## Eolian Deposits

Eolian deposits of light colored sand are widespread in eastern Grand Canyon. These deposits are important because they typically overlie the archeologic terraces to a depth of several meters. Such deposits protect archeologic sites from fluvial erosion and they divert the channels of small streams draining the archeologic terraces, causing runoff to pond temporarily before reaching the Colorado River.

The eolian deposits form sand dunes, sand sheets, and other dune-like features that blanket older deposits. For the most part, these are "coppice dunes," the term applied to sand hummocks or mounds that develop around plants, which partially anchor the wind-blown sand (McKee, 1982, p.48-49). In the river corridor, mesquite trees and shrubs are typically associated with the coppice dunes. The dunes form distinctive topographic features ranging in height from a few meters up to 10-20 m. The eolian sand is moderately-well sorted to moderately sorted and very-fine to fine grained. Average silt and clay content is 5 percent with a range of 2-9 percent; this contrasts with alluvium, which typically has an average silt and clay content of 7 percent with a range of 2-16 percent.

The alluvial deposits of the river corridor are the immediate source of eolian sand; sand that initially comprised the suspended sediment load of the Colorado River. Eolian deposits typically occur downwind of sand flats formed on gravel bars, downwind of a terrace rise, or parallel with a terrace rise. Eolian erosion is enhanced where alluvial deposits are directly exposed to the wind, either by having large surface area or by exposure of sand in steep banks. The sand flats provide the fetch necessary for wind erosion, and a terrace rise exposes sand along the steep bank.

The dune-forming eolian sand deposits post-date the pueblo alluvium (fig. 2), although eolian deposits contemporaneous with the pueblo alluvium are present locally. Thus, the dune activity was probably initiated by erosion and channel adjustment that ended aggradation of the pueblo alluvium. This adjustment resulted in exposure of sand-covered gravel bars and exposed pueblo alluvium in cutbanks. This process continued with subsequent incision of the upper mesquite terrace, which also exposed sand to wind erosion.

Exposure of archeologic material occurs through wind erosion. Eolian erosion, however, is localized, and a balance between exposure and burial probably exists, because the eroded sand is deposited a short distance downwind. Moreover, this type of erosion is initiated to some extent by fluvial undercutting, which cuts steep banks, exposing sand that is readily deflated.

## Geomorphology and Historic Erosion of the Pre-dam Terraces

As previously discussed, stratigraphic evidence indicates that significant erosion of deposits in the river corridor occurred at least twice in prehistoric times, between A.D. 300-700 and between A.D. 1200-1400. This erosion, moreover, was caused by downcutting and major lateral movement of the river channel. In this section of the report, geomorphic information is used to address erosion of the pre-dam terraces and archeologic sites in historic times, or since about 1890. Results indicate that erosion in the past century occurred without significant movement of the river channel; rather, it resulted from the fluvial activity of short tributary streams that drain the river corridor. This type of erosion began as early as 1890, and quite likely increased after 1965-73.

Field observations suggest that the erosional processes discussed here are active wherever the prehistoric to historic alluvial deposits occur in Glen, Marble, and Grand canyons. Of the 475 known archeologic sites, 50 percent (238) are associated with alluvial deposits, and about 52 percent (123) of these sites are presently effected by arroyo cutting in small tributary streams (Fairley and others, 1991). Erosion will continue to effect the 123 archeologic sites plus an undetermined number of the remaining 115 sites present on the alluvial terraces. If results from eastern Grand Canyon are representative, increased depth and extent of arroyo cutting are eventually possible in perhaps 80 percent of the streams draining the terraces, the consequence of tributary-channel adjustment to post-dam conditions. Moreover, in the short term, 20 percent of the streams are particularly susceptible to increased arroyo cutting because of large catchment area and position of the drainage relative to the river.

### Drainage of the Pre-dam Terraces

Small tributary streams that occupy entrenched channels drain the terraces and debris-flow fans of the river corridor as well as bedrock adjacent to the corridor. These streams are ephemeral and flow in direct response to rainfall. The streams are important erosional geomorphic elements of the river corridor, because as they develop, older deposits containing archeologic remains are eroded . The entrenched channels result from runoff and erosion that occurs from rainfall in and adjacent to the river corridor, unlike the Colorado River alluvial deposits which result from events that occur outside the corridor.

The drainage pattern of channels on the terrace of the pueblo and striped alluviums is shown in Plates 1-4. These maps portray the channel system as it existed in October 1989 (except Upper Unkar which dates from October 1984), which is the date of the low-altitude aerial photographs from which the maps were made. The typical channel is entrenched between 0.5 to 5-7 m into the striped and pueblo alluviums, and the channel is flat-floored with a roughly U-shaped cross-section. In the Southwest United States, this type of channel is widespread and occurs across a large range of spatial scales; it is commonly referred to as an "arroyo" (Graf, 1988, p. 218-229), and the erosional activity of these streams is termed "arroyo cutting."

The channels and associated arroyos are categorized by the height of their effective baselevel. In this report, "effective baselevel" (or simply "baselevel") is defined as the local, temporary baselevel of erosion of a particular stream. Effective baselevel corresponds with the level of sand deposition by the Colorado River during a particular discharge regimen. Baselevel is important because it affects the depth of arroyo cutting

Streams that drain to the Colorado River are referred to as "river-based streams, channels, or arroyos;" they are portrayed on Plates 1-4 with heavy lines without arrows. Streams that do not drain to the river are referred to as "terrace based;" they are portrayed on Plates 1-4 with heavy lines ending with arrows. Eleven river-based streams and 44 terrace-based streams that drain the prehistoric terraces are identified on the four maps (Plates 1-4). Assuming these relative proportions are representative of the entire river corridor, we expect that 80 percent of the streams draining the prehistoric alluvium are terrace based and 20 percent are river based. In addition, as discussed in a following section, 25 percent of the terrace-based streams are potentially unstable and will undergo intensified arroyo cutting in the short term, although all of the terrace-based streams have the potential for increased arroyo cutting.

The same erosional processes operate in terrace- and river-based streams; the streams differ primarily in their effective baselevel and catchment areas. Both are ephemeral streams that flow in direct response to rainfall on the terraces and on the nearby hillslopes. Rainfall and the resulting runoff are the direct cause of erosion in these channels. Although archeologic remains are not present in every channel, each channel has the potential to expose archeologic features through widening, deepening, and expansion of the channel system.

The effective baselevel of terrace-based streams is controlled largely by the geomorphology of the river corridor. These streams drain to an older and higher depositional level of the Colorado River. In most cases, this is a relatively flat terrace or terrace-like feature. For example, in the Lower Tanner Canyon area (Plate 2), the effective baselevel of most of the terrace-based streams is the upper mesquite terrace between 807-808 m elevation, which is 5-7 m above the river. The sand dunes in this area, shown topographically by the closed 808-809 m contours, block drainage to the Colorado River. In the Tanner Canyon area east of the river (Plate 3), the large terrace-based stream drains to the surface of a gravel bar at 807-808 m elevation, which is 4-5 m above the river. In the Palisades Creek area (Plate 4), terrace-based streams typically drain to the surface of the pre-dam alluvium at an elevation of 820-822 m on the north side of the Palisades Creek debris-flow fan.

## Catchment Area and Channel Length

In addition to effective baselevel, river and terrace-based streams differ in catchment area and channel length. Figure 5 shows the cumulative frequency distributions of catchment area (fig. 5a) and channel length (fig. 5b) of river and terrace-based streams. The median catchment area of river-based streams is about 16,000 $m^2$, 12 times larger than the median size of terrace-based streams, which is about 1,300 $m^2$ (fig. 5a). Moreover, 63 percent of the terrace-based streams are smaller than the smallest river-based stream, which is about 3,000 $m^2$. Variation in the size of river-based catchments is less than one order of magnitude, whereas the size of terrace-based catchments ranges over three orders of magnitude. The difference in channel length (fig. 5b) is similar to the difference in catchment area. River-based streams have longer channels with less variation in length than channels of terrace-based streams. The median channel length of a river-based stream is about 220 m, whereas the median terrace-based channel is only 60 m.

These differences in catchment area and channel length between stream types suggest that only the larger catchments are capable of establishing through-flowing drainage to the Colorado River. Catchment size is important

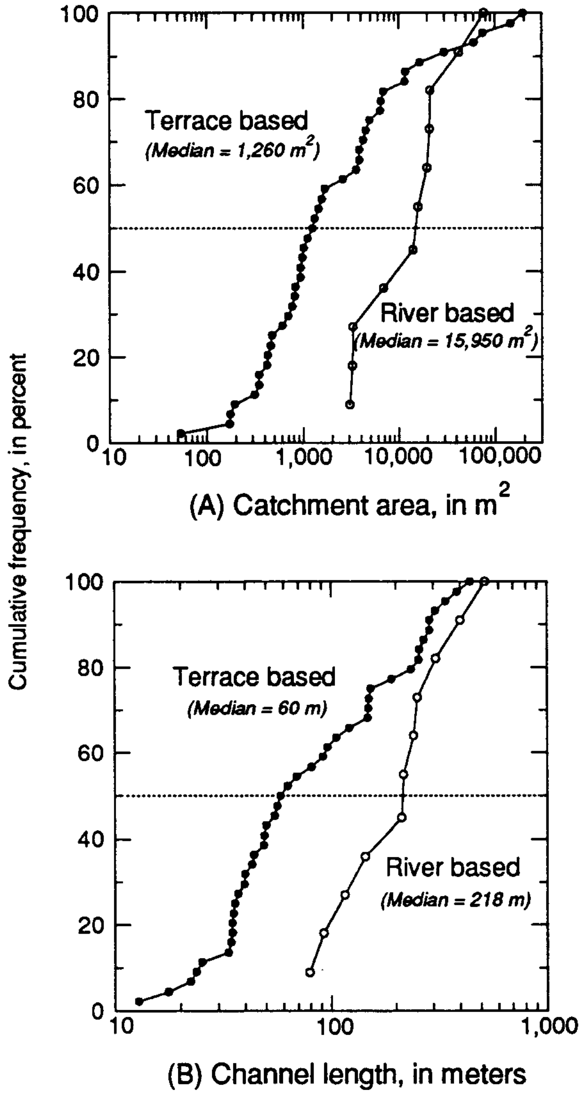



**Figure 5. Cumulative frequency distributions of catchment area (A) and channel length (B) of river-based and terrace-based streams.**

because area is directly related to runoff volume, peak-flow rates, and sediment yield (Graf, 1988, p. 75-82; 120-138). Runoff is also affected by the infiltration characteristics of the catchment. Bedrock (Dox Formation) is present in the headwaters of the larger catchments where it typically constitutes less than 10-50 percent of basin area; otherwise the streams originate on and flow across unconsolidated deposits of sand and gravel, which are relatively permeable.

The bedrock is broken by numerous, essentially vertical fractures that are typically only a few centimeters apart. These fractures and the platy character of the Dox increase the permeability of the formation, which reduces runoff. Thus, the contrast in permeability between bedrock and unconsolidated sediment might not be large. The infiltration characteristics of the typical catchment, therefore, are probably those of the unconsolidated deposits, because bedrock constitutes a small portion of most catchments and bedrock is at least moderately permeable.

A catchment area of 3,000 $m^2$ is possibly the minimum necessary to generate the water and sediment runoff needed to establish through-flowing drainage, particularly where the distance to the river is short. Terrace-based streams larger than 3,000 $m^2$ are potentially capable of generating sufficient runoff to establish through-flowing drainage, and catchments in this size range are probably unstable, unless distance to the river is large.

Experimental evidence and field observations show that imposition of a lower baselevel initiates a wave of erosion that extends upstream throughout the catchment (Chorley and others, 1985, p. 334-335). This channel erosion is typically associated with an increase in the size and shape of the drainage basin (Gregory and Walling, 1973, p. 366-369). Any terrace-based stream can probably degrade to the lower effective baselevel of the post-dam era through downcutting and subsequent expansion of the drainage network, increasing catchment area and channel length. This expansion process and increased arroyo cutting probably decline after the stream reaches and adjusts to the level of the Colorado River, which explains the relatively uniform channel length and catchment area of river-based streams (fig. 5). The relatively small number of river-based streams might reflect their evolution from terrace-based streams through stream capture and basin enlargement. In other words, the river-based catchments probably develop through integration of several terrace-based catchments.

## Stability of Terrace-based Channels

The terrace-based channels differ substantially in distance from the end of the channel to the river, as shown in Plates 1-4. This and basin area affect the potential of the channel to reach the river, which in turn affects the erosional stability of the channel system. Figure 6 shows distance to the river of the terrace-

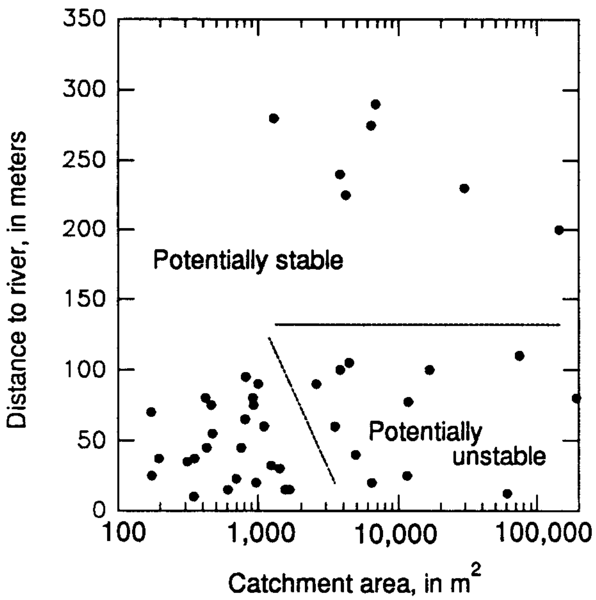



**Figure 6. Stability fields of terrace-based streams as a combination of catchment area and distance to the river.**

based channels plotted against basin area. Distance was measured from the end of the stream symbol to the river following the topographic slope along incipient channels and other low-lying areas, which is not necessarily the direct path to the river. Two fields are distinguishable in figure 6 that probably correspond with stable and unstable combinations of catchment area and distance to the river. Potentially unstable channels have relatively large catchment area, and the channels end near the river. The area of these potentially unstable basins is greater than 3,000 $m^2$, and the channels end within about 10-100 m of the river.

In the short term, these channels are probably the least stable, because catchment size is large enough to produce the runoff volume needed to establish a channel across the relatively short distance to the river. About 25 percent of the studied catchments are potentially unstable. Assuming that the studied catchments are representative of others in the river corridor, then about 25 percent of all terrace-based channels are also potentially unstable.

Once the channel reaches the river, the gradient will adjust to the lower baselevel, increasing erosion throughout the catchment. Preventative erosion-control measures could be considered for this class of terrace-based stream, because over the short term they are the most susceptible to change and will probably cause the most erosive damage.

Potentially stable terrace-based channels occur as two combinations of catchment area and distance to the river. In one case, channels are relatively close to the river, but basin area is probably too small to generate significant runoff volume (lower left portion of fig. 6). In the other case, catchment area is large, but the distance to the river is also large, between 200-300 m (upper right portion of fig. 6). During a storm runoff volume from these catchments is large; however, the substantial distance to the river makes it unlikely that a particular channel will reach the river.

## Historic Development of the Drainage System

Arroyos have probably developed episodically throughout the late Holocene in eastern Grand Canyon, although evidence of prehistoric to protohistoric arroyos is lacking. The most recent arroyos date from about 1890 until the present. Field relations show that the arroyos post-date the deposits of the striped, pueblo, and upper mesquite terrace alluviums, as the arroyos are entrenched into these deposits. In addition, photographic evidence from the Tanner Canyon and Palisades Creek area suggests that arroyos were not present in 1890.

In the Tanner Canyon area (fig. 1), a photograph taken in January 1890 (R.H. Webb, 1990, personal communication, stake number 1742; Stanton number 391) shows the terrace of the striped alluvium west of Tanner Canyon (Plate 3). The photograph was taken on a hillslope 34 m above the river; it is a view to the southwest with the terrace of the striped alluvium in the center foreground. The map of this area (Plate 3) shows the distinct southwest-trending terrace rise between the 810-820 m contours. The prominent north-trending arroyo with headwaters in the hillslopes near 890 m elevation is not present in the 1890 photograph. The two smaller arroyos west of the large north-trending arroyo are also not present in the photograph.

Another photograph taken in 1890 shows that arroyo cutting had not yet effected the river corridor immediately north of Palisades Creek (fig. 1). The photograph (R.H. Webb, 1990, personal communication, stake number 1434a; Stanton number 384) was taken about 50 m above the river and is a view to the west-southwest across the Colorado River to the mouth of Lava Canyon (fig. 1). The terrace of the striped alluvium on the east side of the river upstream of the rapids is present in the center foreground of the photograph. The map of this area (Plate 4) shows the terrace rise of the pueblo alluvium west of the Beamer Trail between the 820-825 m contours. The terrace is dissected by six arroyos; three of these are visible from the relocated photographic station, but none are present in the 1890 photograph. This evidence suggests that the arroyos on the prehistoric terraces have developed since 1890.

Exactly when arroyo cutting began after 1890 in eastern Grand Canyon is difficult to determine. To show these relatively small features, ground-based or low-altitude aerial photographs are necessary. Ground-based photographs must be taken from above the river at a relatively high angle, such as the Stanton photographs, which were taken to illustrate the topography of the river corridor. Literally thousands of photographs have been taken by river runners in Grand Canyon. In most cases, however, these photographs are not useful because they are typically taken at river level from a low angle, and they are difficult to obtain because they are not systematically archived. Low-altitude aerial photographs are the most useful source of information, but the first low-altitude survey of the canyon was done in 1965.

Photographs taken during scenic overflights of the Grand Canyon are potentially useful, but these are widely scattered in personal photograph collections. A low altitude oblique-aerial photograph, however, on the front cover of the June 1958 *Arizona Highways* shows the mouth of Cardenas Creek and the Upper Unkar area (fig. 1). The large arroyo on the east-half of the Upper Unkar map (Plate 1) that trends north from the river with a northeast bend to the headwaters at 835 m is present in the photograph. This is the largest and deepest arroyo on the pueblo terrace, and it was entrenched before June 1958.

Table 1 lists the low-altitude aerial photographs examined for evidence of arroyo development. Generally, most of the larger arroyos shown on Plates 1-4 are present in the photographs of May 1965. The major arroyos of the present drainage system appear to have been in place by at least 1965, if not before June 1958.

**Table 1. Low-altitude aerial photography examined for evidence of arroyo development**

| Date Source | Scale | Number | Area |
|---|---|---|---|
| 5/14/65 | 6,000 | 135 | Upper Unkar |
| WRD[1] | | 133 | Lower Tanner Canyon |
| | | 132 | Tanner Canyon |
| | | 123 | Palisades Creek |
| 6/16/73 | 7,200 | 182 | Upper Unkar |
| WRD | | 177-179 | Lower Tanner Canyon |
| | | 175 | Tanner Canyon |
| | | 168 | Palisades Creek |
| 6/27/80 WPRS[2] | 3,600 | 14-04 | Upper Unkar |
| 7/11/80 | 3,600 | 12 & 13-08 | Lower Tanner Canyon |
| WPRS | | 13-09 | |
| | | 12 & 13-05 | Tanner Canyon |
| 10/22/84 | 3,200 | 3-123 | Upper Unkar |
| GCES[3] | | 3-114 to 117 | Lower Tanner Canyon |
| | | 3-110 to 113 | Tanner Canyon |
| | | 3-80 to 84 | Palisades Creek |

[1] Water Resources Division, U.S. Geological Survey

[2] U.S. Department of Interior, Water and Power Resources Service (Bureau of Reclamation)

[3] Glen Canyon Environmental Studies, U.S. Bureau of Reclamation

The photographs of June 1973 show no detectable change in the size or number of arroyos; however, the June 1980 photograph of the Upper Unkar area shows several shallow depressions, which were not present in 1973, that cross the terrace rise of the pueblo alluvium west of the previously discussed large arroyo. These incipient arroyos were well developed by October 1984, as shown in Plate 1. In all cases, a striking change occurs between the 1973 and 1984 photographs. The arroyos appear to have been recently deepened, channels have extended headward, and new arroyos are present. In summary, the major elements of the drainage system of the prehistoric terraces developed sometime after 1890 and probably long before June 1958. The drainage system appears to have been little affected by arroyo cutting from as early as 1958 to at least 1973; after which arroyo cutting intensified.

## Evidence of Arroyo Cutting and Erosion Since 1973

Observations over several field seasons beginning in October 1989 indicate that most of the small streams actively erode during large rainfall events. The longitudinal profile of most channels has one or more nickpoints. A nickpoint is a local steepening of the profile where increased water velocity accelerates and concentrates erosion. Near the nickpoints, evidence of erosion is fresh, and buried or surface archeologic features, if present, are undergoing erosion and exposure.

The nickpoints are evidence of channel rejuvenation and adjustment to a disturbance. Nickpoints migrate headward during streamflow, which lowers the channel gradient downstream of the nickpoint and widens the channel through bank collapse. In the terrace-based streams, the disturbance is large runoff caused by excessive rainfall, and in the river-based streams the disturbance is runoff as well as the lower baselevel of the post-dam era. In either type of stream, rainfall and runoff are necessary for nickpoint migration and erosion.

Nickpoints are shown on the topographic maps (Plates 1-4) where a stream symbol crosses closely spaced contours. At the Lower Tanner Canyon area (Plate 2), active nickpoints are present in the channels at the terrace rise between 808-810 m elevation where terrace-based streams cross a coppice dune field. Figure 7 shows a nickpoint and prominent headcut in a terrace-based stream at this locality. A metate, or grinding stone, is exposed to the left of the person. Rainfall in September 1992 produced sufficient runoff to cause about 0.5 m upstream movement of the headcut, which dislodged the artifact. This headcut developed sometime after 1973 when the stream breached the dune field in the low area between sand mounds, which demonstrates that the coppice dunes are only temporary barriers to downslope extension of terrace-based streams.

In the Tanner Canyon area east of the Colorado River (Plate 3), one or more actively migrating nickpoints are present where channels descend the west-facing terrace rise of the striped alluvium between 810-820 m elevation. At the Palisades Creek area (Plate 4), streams draining the north side of the Palisades Creek debris-flow fan steepen where they descend the pueblo terrace rise between 820-826 m; on the south side of the fan, they steepen between 820-822 m.

This ongoing nickpoint migration was probably initiated by an episode of intense arroyo cutting that began after 1973, as suggested by comparison of low-altitude aerial photographs (table 1). At two areas, Upper Unkar and Palisades Creek (fig. 1), abundant photographic information details the timing and magnitude of arroyo cutting between 1973 and 1984.

Erosion of the Upper Unkar area is documented by comparison of photographs taken by Robert C. Euler in 1965, 1972, and 1978 with photographs of the same areas taken in 1983 and 1991. These photographs provide evidence of arroyo cutting and erosion of archeologic features by the short tributary streams that drain the river corridor. The photographs are shown in figures 8 and 9. Figure 8a was taken by Euler on June 4, 1965. The approximate location of the photograph station is labelled RCE PS 1 on Plate 1. The view is to the west-northwest across an arroyo that is about 6 m deep. The area lies within locality 1 of Jones (1986, p. 74) and contains 3 structures and 13 features. Another Euler photograph of this area was taken July 11, 1978. The photograph was not relocated, as it was taken from a different perspective and some distance to the left of figure 8a. The 1978 photograph is difficult to compare directly with figure 8a, but the walls of the structure are not present in the photograph.

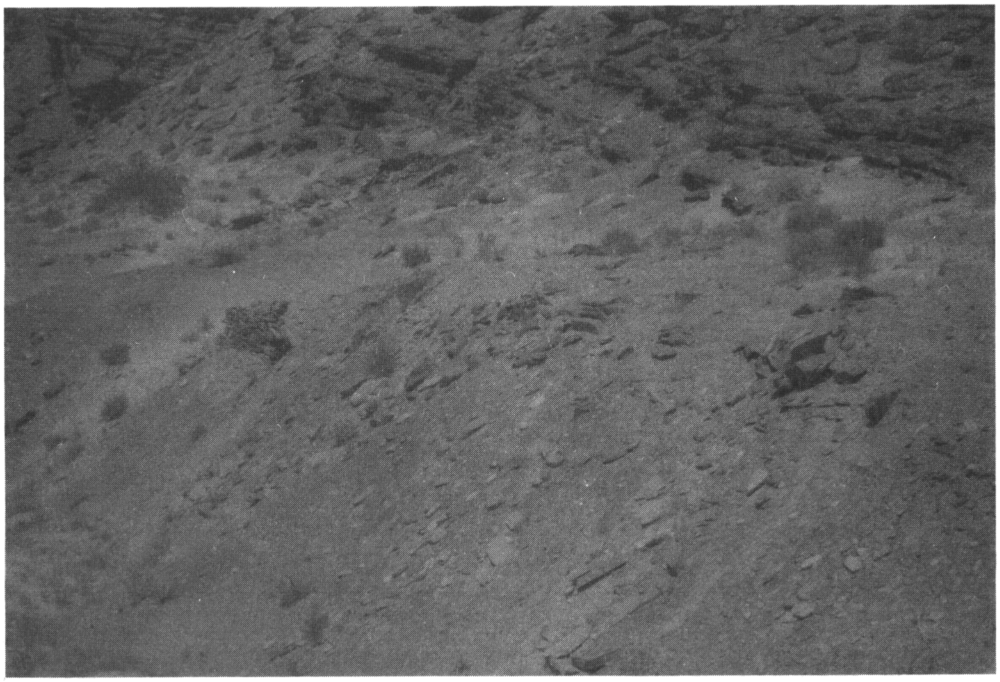
A photograph taken November 16, 1991 from very close to the Euler photograph site is shown in figure 8b. The arroyo has deepened and widened since 1965, causing extensive damage to the archeologic site. The wall to the left of center in the Euler photograph (fig. 8a) had collapsed (this occurred by July 11, 1978), and the blocks were removed by erosion (fig.

**Figure 7. Headcut exposing a metate (grinding stone) in the arroyo of a terrace-based stream in the Lower Tanner Canyon area (fig. 1; Plate 2) in November 1990. The metate was dislodged during runoff and headcut migration in September 1992. The headcut occurs in a low area between two sand mounds of a coppice dune field.**

8b). This erosion produced a small, steep arroyo beneath the wall. Other structures present in the central portion of the Euler photograph (fig. 8a) have also collapsed and were removed by erosion. This was evidently caused by widening of the north side of the arroyo. The flat, terrace-like surface between approximately the 811-813 m contours (Plate 1) was wider and extended farther south in 1965 (fig. 8a) than at present (fig. 8b). In addition, the Euler photograph (fig. 8a) shows light-colored eolian sand and alluvium in the channel of the large arroyo. These deposits have been eroded since 1965, and bedrock is now exposed in the channel.

Figure 9a was first published in Euler and Taylor (1966); the photograph was taken on June 4, 1965. The approximate location of the photograph site is labelled RCE PS 2 on Plate 1. The view is northwest and the photograph shows the terrace rise or scarp of the pueblo alluvium defined by the 806-812 m contours (Plate 1). The area lies in locality 2 of Jones (1986, p. 75) who identified two structures and three features within the field of view. Figure 9b was taken by Janet R. Balsom on September 15, 1983. The Balsom photograph was taken about 5 m to the left of the Euler photograph with a lens of shorter focal length. Nonetheless, the Balsom photograph is comparable with the Euler photograph, although comparison requires scrutiny of the background and allowance for different camera focal length and location.

In 1965, the terrace rise was relatively undissected (fig. 9a), although a subdued, apparently inactive channel is present in the left center of the photograph. Between 1965 and mid-September 1983, the terrace rise was dissected substantially, as shown by the fresh appearing arroyo in the center of the Balsom photograph (fig. 9b). As previously discussed,



(A)

(B)

**Figure 8. Repeat photographs of locality 1 (Jones, 1986, p. 74) in the Upper Unkar archeologic area showing erosion of archeologic features. (A) Photograph by Robert C. Euler, June 4, 1965, and (B) approximately the same scene, November 16, 1991.**

(A)

(B)

Figure 9. Repeat photographs showing arroyo development and erosion of archeologic features at locality 2 of Jones (1986, p.75). (A) Photograph by Robert C. Euler, June 4, 1965. (B) Photograph of approximately the same area by Janet R. Balsom, September 15, 1983.

the incipient form of these arroyos is present in the 1980 aerial photographs (table 1). This erosion exposed and damaged several archeologic features that were later excavated by Jones (1986). The terrace in the foreground of figure 9b is the pre-dam alluvium (unit pda of fig. 2) with a thin cover of eolian sand with asymmetric ripple marks.

The area north of the Colorado River in the east quarter of the Upper Unkar area (Plate 1) was photographed by Euler in May 1972. This photograph and a duplicate taken from about the same spot in March 1992 are shown in figure 10. The wall present in figure 8b is also present in the extreme left portion of figure 10a; it is extremely small in this photograph because of the large distance, but the wall is visible to the right of the light-colored area on the arroyo wall facing the camera. The area that slopes toward the river between the dark bedrock on the left and the large wash on the right is smooth and largely unaffected by arroyo cutting. Figure 10b, taken in March 1992, shows that the surface has been heavily eroded, and a well-developed channel system is present. The baselevel of the newly developed channel system is controlled by bedrock, and erosion of these channels is unrelated to the level of the Colorado River. In addition, the mouth of the large wash on the right side of the photograph has a small, well-formed debris-flow fan and rubble from the debris flow is present in the river (fig. 10b).

The channel system, debris-flow fan, and debris-flow rubble in the river form conspicuous topographic elements on the east side of the Upper Unkar map (Plate 1) between the large arroyo of the archeologic site and the mouth of the large wash on the east side of the map, which was made from the 1984 aerial photographs (table 1). The arroyo system and debris flow are not present in the 1980 aerial photographs of the Upper Unkar area (table 1). Dissection of this surface and emplacement of the debris-flow fan and rubble took place between June 27, 1980 and October 22, 1984.

In the Palisades Creek area (fig. 1), comparison of low-altitude aerial photographs (table 1) documents entrenchment of existing arroyos and development of new arroyos. The 1965 aerial photographs show several of the present arroyos, including the two river-based arroyos south of Palisades Creek and three or possibly four of the 12 arroyos north of Palisades Creek. In 1965 and 1973, the arroyos appeared subdued and relatively shallow compared with the same arroyo in aerial photographs taken in October 1984. The sides of the arroyos in 1965 and 1973 had relatively low albedo, suggesting that the arroyos were stable; in 1984, however, the sides were steep and had high albedo, indicating recent erosion.

The two arroyos south of Palisades Creek (Plate 4) had terrace-based channels in 1965 and 1973 that ended at the terrace of the pre-dam alluvium near the 821 m contour. By 1984, two well-developed channels were present extending from near the 821 m contour to the Colorado River. This occurred by downstream erosional extension of the channels. Both channels have extended downstream by about 80 m. The resulting arroyos are up to 4 m wide and 1-2 m deep. In addition, the arroyos are presently deeper, wider, and longer.

This channel expansion appears to be unrelated to human activity such as development of hiking trails or to breaching of the playa which forms the headwaters of the southernmost of the two streams. The channels are not aligned along trails; the main trail in this area crosses the channels at right angles (Plate 1), and the aerial photographs show no increase in the number or length of trails. The channel of the southernmost stream was incised into the playa in 1965, while the stream was still terrace based.

Figure 11 is a time line showing fluvial activity of eastern Grand Canyon in terms of stability and arroyo cutting as inferred from the aerial photographs, ground-based photographs, and observations discussed previously. This evidence suggests that the tributary streams were stable from June 1958 through June 1973. The arroyo cutting evident in the 1984 aerial photographs was probably underway before June 1980, and possibly underway before July 1978 when a photograph shows erosion of the wall at Upper Unkar. Based on this evidence, arroyo cutting began sometime between June 1973 and July 1978. Climate evidence presented in a following section suggests that arroyo cutting probably began in the fall to winter of 1977-78. The aerial photographs show little change between October 1984 and October 1989; thus, arroyo cutting was largely

(A)

(B)

**Figure 10. Repeat photographs showing dissection and arroyo development on the north side of the Colorado River in the east portion of the Upper Unkar area (Plate 1). (A) Photograph by Robert C. Euler, May 1972. (B) Approximately the same scene in March 1992.**

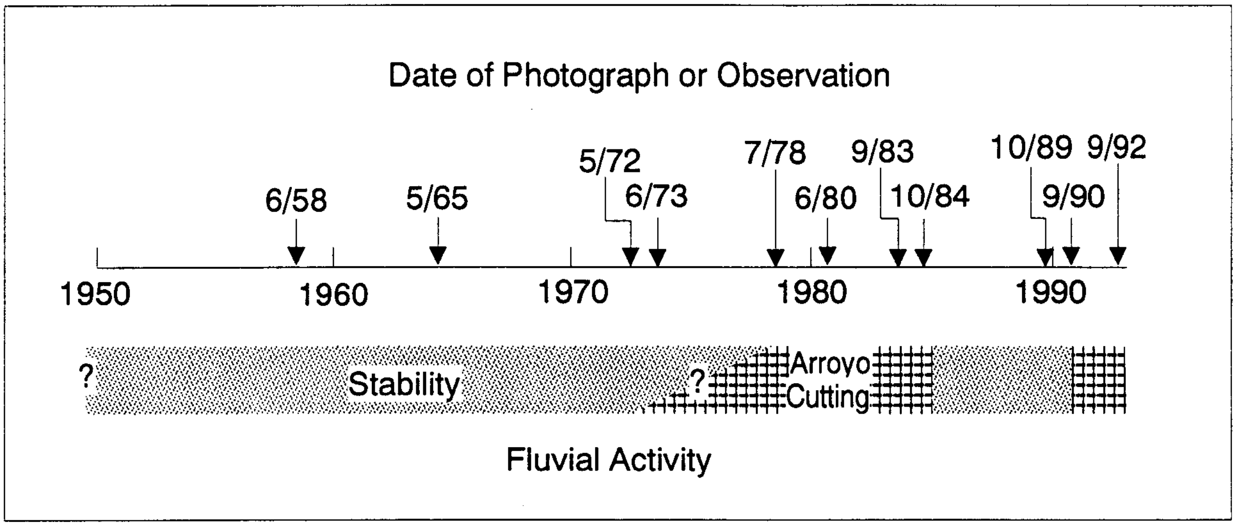



**Figure 11. Time line showing fluvial activity in terms of stability (no change) and arroyo cutting based on dates of photographs and field observations.**

over by October 1984. This period of stability lasted until September 1990, when renewed erosion was observed throughout the area.

In short, arroyo cutting has increased since at least June 1973. Arroyos that appeared stable between 1965-73 have since widened, deepened, and extended upstream and downstream, resulting in the loss of archeologic sites. New arroyos have developed leading to further dissection of pre-historic terraces. After almost 6 years of stability, erosion has renewed, as channels show evidence of erosional activity in the past several years.

## Effective Baselevel of the Pre- and Post-Dam Eras

The increased arroyo cutting after 1973 was initiated by unusually heavy rainfall, as described in a following section. In some cases, the intensity of arroyo cutting was quite likely exacerbated by the reduced effective baselevel of the post-dam era. This is true of all streams that changed from terrace based to river based. The number of such changes is difficult to determine, because this would require photogrammetric analysis and reconstruction of the aerial photography (table 1). Nevertheless, the presence of terrace-based streams ending on the terrace of the pre-dam alluvium at Palisades Creek in 1965 suggests that the terrace was the baselevel of the late pre-dam and early post-dam eras. This suggests that all of the present river-based streams could have been terrace based in the latest pre-dam era. Periodically, however, terrace-based streams of the pre-dam era could have flowed to the river and initiated arroyo cutting.

Table 2 shows the elevation of the terrace of the youngest pre-dam alluvium (unit pda of fig. 2) and the elevations of the post-dam channel side bars (units fs, hf, and ff of fig. 2). The elevations are based on the mapped distribution of the deposits, as compiled from the October 1989 aerial photographs onto the four topographic base maps. These deposits, as previously discussed, record the depositional level of the Colorado River since 1983, as the channel side bars date from the flood of 1983. If the fluctuating flow sand is taken as the long-term, post-dam depositional level, then the level of the Colorado River is now about 3-4 m below the pre-dam level as represented by the pre-dam alluvium. This range of 3-4 m is obtained by subtracting the mid-point elevation of the fluctuating flow sand from the mid-point elevation of the pre-dam alluvium.

## Stream Entrenchment and Effective Baselevel

Baselevel control of a typical arroyo is illustrated in figure 12, which is a cross-section showing the relation between the longitudinal profile of the channel and the various depositional levels of the Colorado River. This

**Table 2. Elevation of the pre-dam alluvium and post-dam channel side bars at the four study areas (fig. 1) showing decrease of effective baselevel and depositional level of the Colorado River**

| Area | Elevation (m) | | | | |
|---|---|---|---|---|---|
| | pda[1] (1) | fs[2] (2) | hf[3] (3) | ff[4] (4) | Difference[5] (5) |
| Upper Unkar | 804-805 | 803-804 | 802-803 | 800-801 | 4 |
| Lower Tanner Canyon | 805-806 | 804-805 | 803-804 | 802-803 | 3 |
| Tanner Canyon | 807-808 | 805-806 | 804-805 | 803-804 | 4 |
| Palisades Creek | 820-821 | 818-819 | 817-818 | 816-817 | 4 |

[1] Pre-dam alluvium

[2] Flood sand of summer 1983

[3] High flow sand

[4] Fluctuating flow sand

[5] Difference is obtained by subtracting the middle elevation of column 4 from the middle elevation of column 1

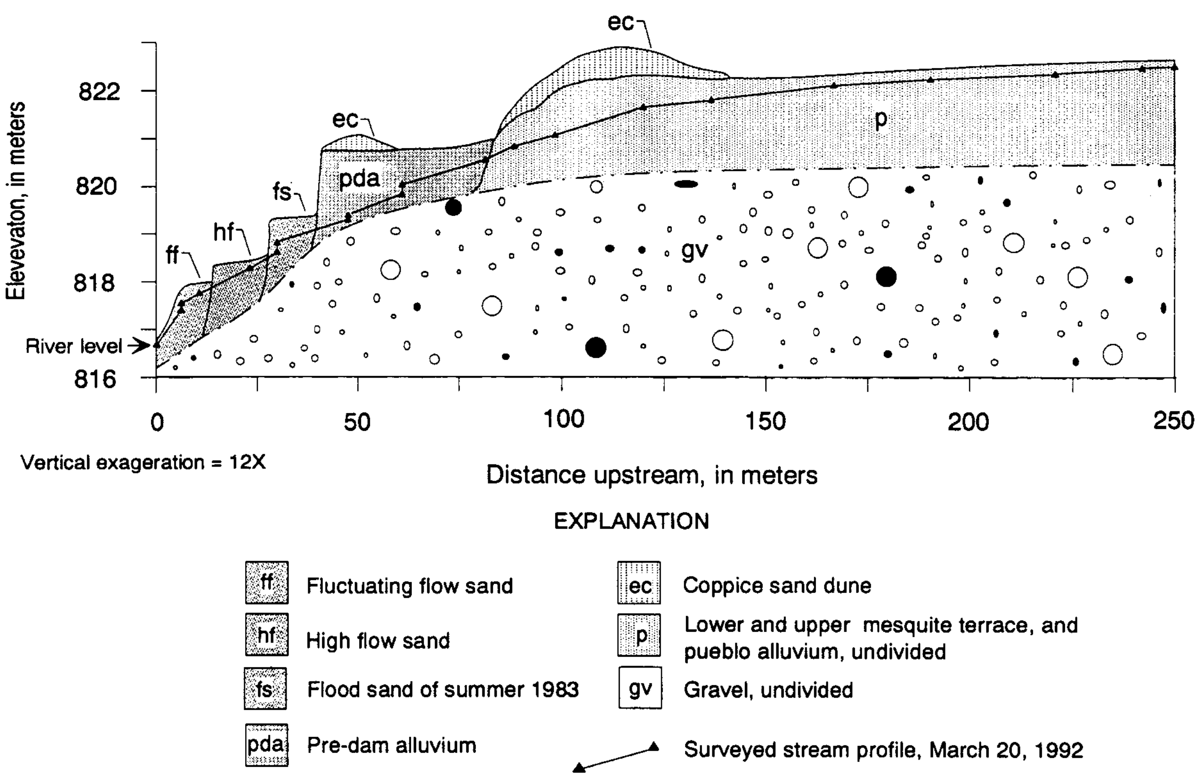



**Figure 12. Cross-section showing baselevel control and longitudinal profile of a river-based stream in the Palisades Creek area.**

arroyo is the southernmost of the two arroyos south of Palisades Creek (Plate 4) whose transition from terrace based to river based after 1973 was discussed in a preceding section. The present area of the this catchment is 19,600 $m^2$.

The channel has four headcuts between the river and about 75 m upstream of the river which are 20 cm high. Field observations show that the headcuts moved up the channel several meters during runoff in the summer of 1990 and 1992. In addition, the channel gradient is steep without significant headcuts between 75-150 m upstream (fig. 12). The average gradient upstream of about 150 m projects downstream to near the top of the pre-dam alluvium. This suggests that the oversteepening of the channel between 75-150 m resulted from downcutting through the pre-dam alluvium. The gradient of the oversteepened segment decreases when the nickpoint migrates upstream, which deepens the channel.

Sometime after 1973, the stream overflowed the edge of the terrace, initiating erosion upstream that deepened and widened the channel. The presence of nickpoints in river-based streams suggests that adjustment to the new, lower baselevel is continuing. Figure 13 illustrates schematically how the lowering of channel profile extends up the channel in the transition from a terrace-based to river-based stream.

## Precipitation in Eastern Grand Canyon in the Post-dam Era

Precipitation in eastern Grand Canyon was analyzed to search for unusual patterns that might correspond in time with the observed changes of fluvial activity (fig. 11). Precipitation is not measured in the study area, although weather stations operate at Cameron, Desert View, Phantom Ranch, and the South Rim. The location, elevation, and period of record of the four stations are listed in table 3. The data consists of daily rainfall measurements collected at the four weather stations, which are operated, except for Desert View, on a cooperative basis with the National Oceanographic and Atmospheric Administration (NOAA, 1986). The data are incomplete because of missing entries ranging from a few days to several years. The Desert View daily precipitation record is available only from 1975, but monthly totals are available since 1960. In the following analysis, a missing value was assigned to any month or season with 10 percent or more missing daily entries.

Annual precipitation in northern Arizona is bi-seasonal with maxima in summer and winter; more than half of the annual total typi-

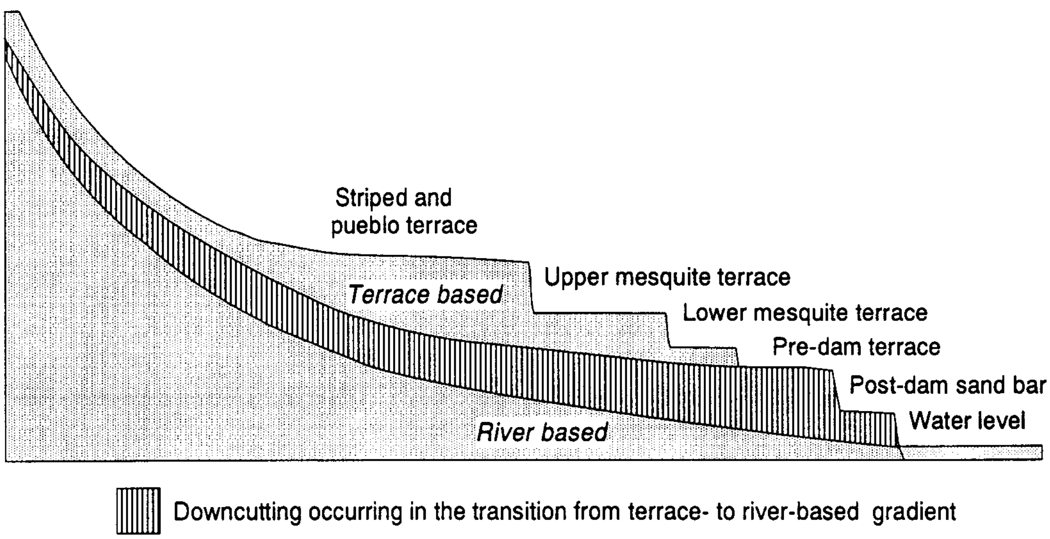



**Figure 13. Schematic cross-section showing longitudinal profile and baselevel of river-based and terrace-based channel and downcutting that occurs in the terrace-based to river-based transition.**

**Table 3. Weather stations of the eastern Grand Canyon region**

| Station | Elevation (m) | Latitude Longitude | Period of Record | Average Annual Precip. (mm) |
|---|---|---|---|---|
| Cameron | 1,269 | $35^0$ 52' $111^0$ 24' | 5/1/1962 7/31/1991 | 177.1 |
| Desert View | 2,267 | $36^0$ 02' $111^0$ 06' | 7/1/1975 8/31/1991 | 354.3 |
| Phantom Ranch | 783 | $36^0$ 06' $112^0$ 06' | 8/1/1966 7/31/1991 | 261.0 |
| South Rim | 2,125 | $36^0$ 03' $112^0$ 08' | 9/1/1903 7/31/1991 | 413.4 |

cally occurs between May and October (Sellers and Hill, 1974, p. 3-19). The winter maximum occurs between December and March. Depending on conditions, this precipitation may occur as rain or snow in the higher elevations, and as rain in the lower elevations such as the river corridor, where average snowfall is only 25 mm $yr^{-1}$ or less (Sellers and Hill, 1974, p. 240). For operational purposes, two seasons were defined: warm-season rainfall of June 15 to October 15, and rain or snow of the fall to winter season, November 1 to February 28. Most of the annual precipitation and all of the known flood-producing events occur in these seasons.

Although the precipitation of individual storms in arid to semiarid regions varies substantially (Graf, 1988, p. 72-74), the pattern of wet and dry months generally prevails over a large area. Figure 14 is a time series of the total monthly precipitation of the four weather stations. Variation from month-to-month and between stations is substantial. The month-to-month variation results largely from the two wet seasons and from the April-June dry season. Station-to-station variation results from local conditions, primarily elevation. On average, the low-elevation stations (table 3; fig. 14) have the least precipitation.

Despite the large monthly variation and variation among the stations, comparison of the time series (fig. 14) shows a similar pattern of peaks and troughs, indicating they are consistent with each other, in most cases. The conclusion is that local rainfall patterns in the study area can be inferred from the rainfall at the four regional weather stations, particularly the occurrence of unusually wet or dry months and seasons.

The precipitation characteristics of seasons known to have produced runoff in eastern Grand Canyon or regionally were analyzed. This analysis was undertaken to identify the daily pattern and amount of precipitation likely to be associated with runoff; unusually dry seasons were also analyzed for comparison of daily patterns and amount of precipitation. The results of this analysis are shown in figures 15-22, which show the day and amount of rainfall for each season with unusual rainfall or portion of a season having significant rainfall.

Three warm seasons were identified, 1990, 1983, and 1972, that were associated with or probably associated with significant runoff in eastern Grand Canyon (figs. 15-18). Runoff and debris-flow activity occurred in eastern Grand Canyon during September 21-24, 1990 (fig. 15). This rainfall produced debris flows in two unnamed drainages between Chuar and Lava Buttes, which deposited coarse rubble in the Colorado River; in addition, runoff and arroyo cutting were widespread in the study area. The runoff and debris-flow activity were the culmination of an extended wet spell that began on September 16 at Desert View. The rainfall around the beginning of September and earlier in mid-August probably resulted in favorable antecedent moisture conditions, which increased runoff during the late September rainfall.

Rainfall during the warm season of 1983 is shown in figure 16. Arroyo cutting had occurred by September 15 at the Upper Unkar locality, as illustrated by the Balsom photograph (fig. 9b). Elsewhere in the study area, Webb and others (1989, p. 36) report debris-flow activity, a rockfall, and floods during 1983, all of which quite likely occurred during the warm season. Rainfall at Desert View (fig. 16a) began on July 5 and continued intermittently until August 21. During this time, rain was recorded on 27 days, and 20 mm or more of rain occurred on four occasions. Rainfall was particularly heavy on July 26 with 20, 47, and 80 mm falling at Desert View, Phantom Ranch, and South Rim, respectively.

Heavy rainfall and runoff were typical in northern Arizona during early to mid-October 1972 (Hereford, 1984). Rainfall in the eastern

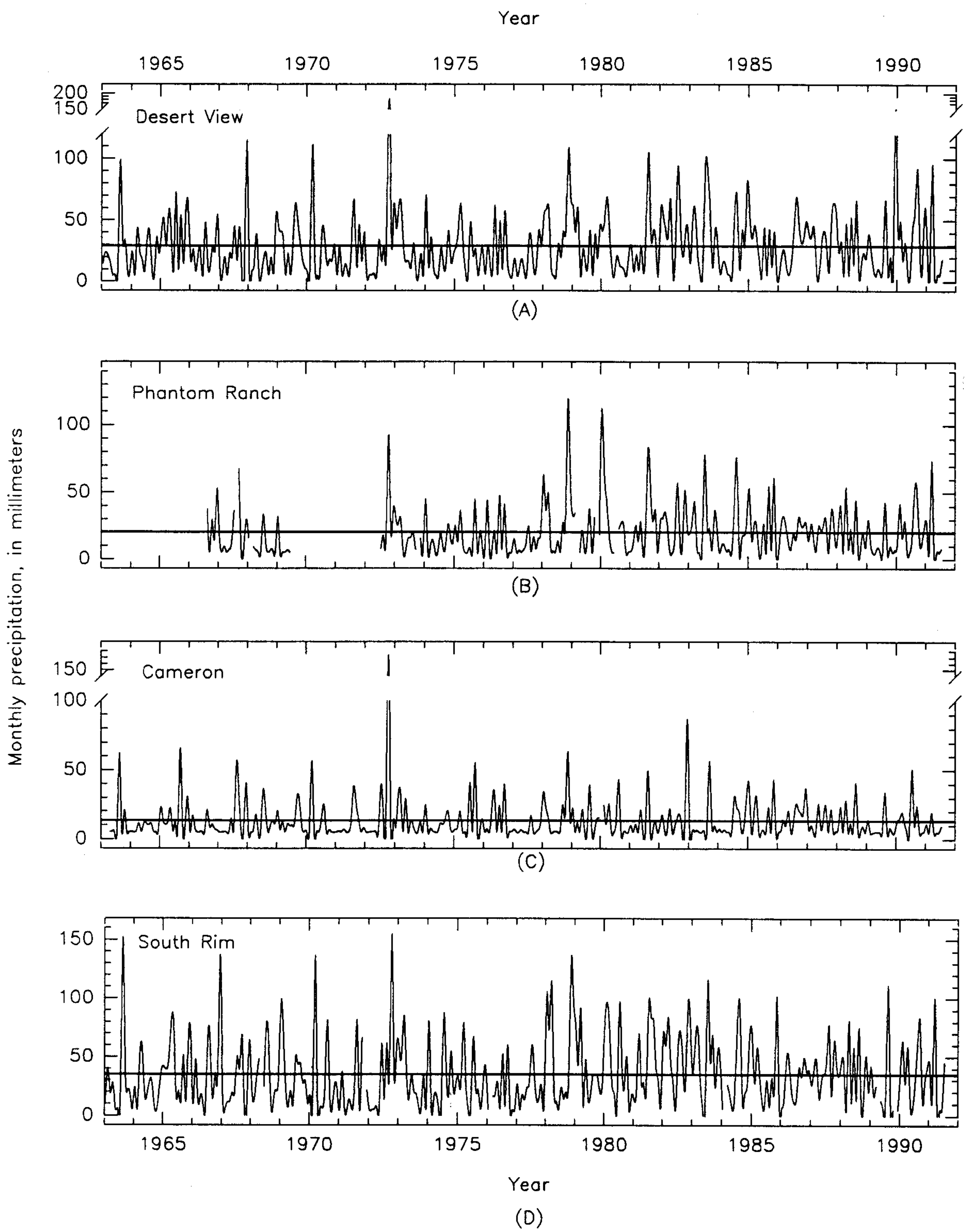



**Figure 14. Total monthly precipitation at the four weather stations (table 3) in the Grand Canyon region, breaks show missing data. Horizontal line is the long-term monthly average. (A) Desert View, (B) Phantom Ranch, (C) Cameron, and (D) South Rim.**

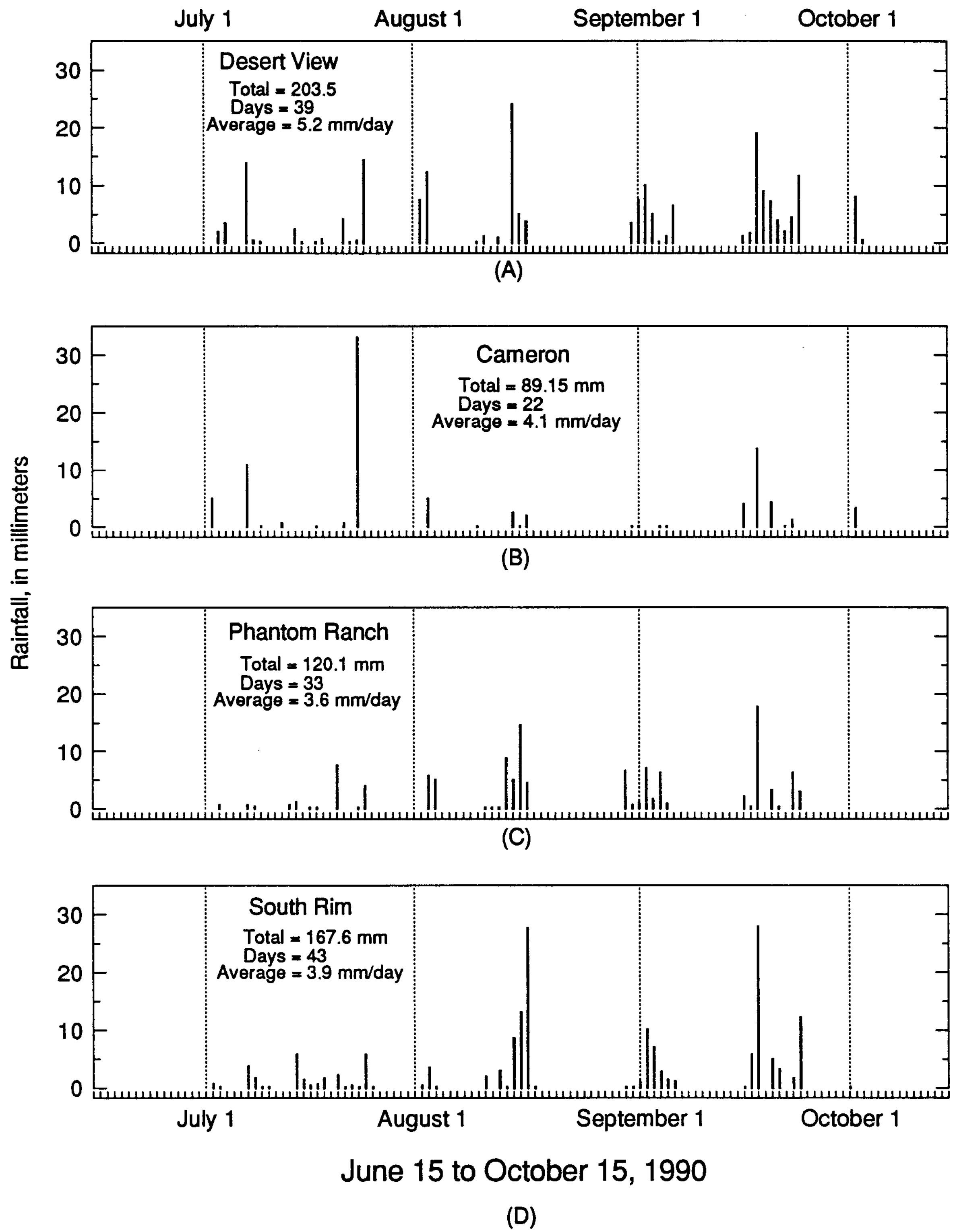



**Figure 15. Warm-season rainfall, 1990, a wet season with runoff and debris-flow activity. (A) Desert View, (B) Cameron, (C) Phantom Ranch, and (D) South Rim.**

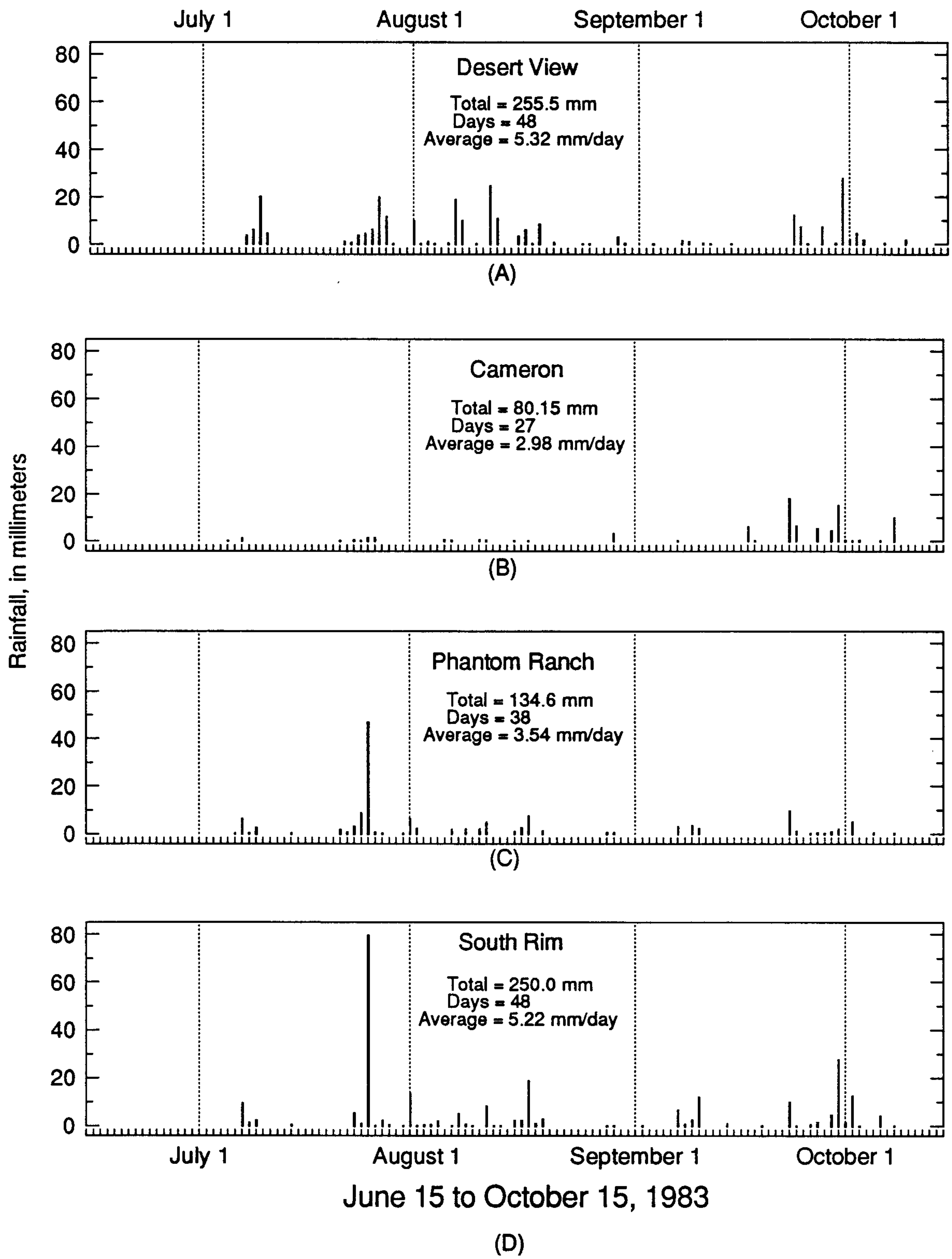



**Figure 16. Warm-season rainfall, 1983, a wet season with runoff and debris-flow activity. (A) Desert View, (B) Cameron, (C) Phantom Ranch, and (D) South Rim.**

Grand Canyon region occurred during two storms, October 3-8 and October 15-21 (fig. 17). October rainfall at Desert View, Cameron, and South Rim was the largest of any month for the period 1963-1991 (fig. 14). Daily amounts in excess of 20 mm occurred several times at each station. The effects of this unusual rainfall are not well known in Grand Canyon, although destruction of the masonry wall at Upper Unkar (fig. 8) might have occurred during October 1972.

Figures 18 and 19 show the daily rainfall of two warm seasons, 1973 and 1977, that were unusually dry. In a dry season, daily rainfall is typically much less than in a wet season (figs. 15-17), although the occurrence of rain is about the same in the case of 1977. Total rainfall of a dry season is about 2-3 times less than a wet season, and daily accumulation is also less. Regionally, the mid-1970s were among the driest warm seasons of the century

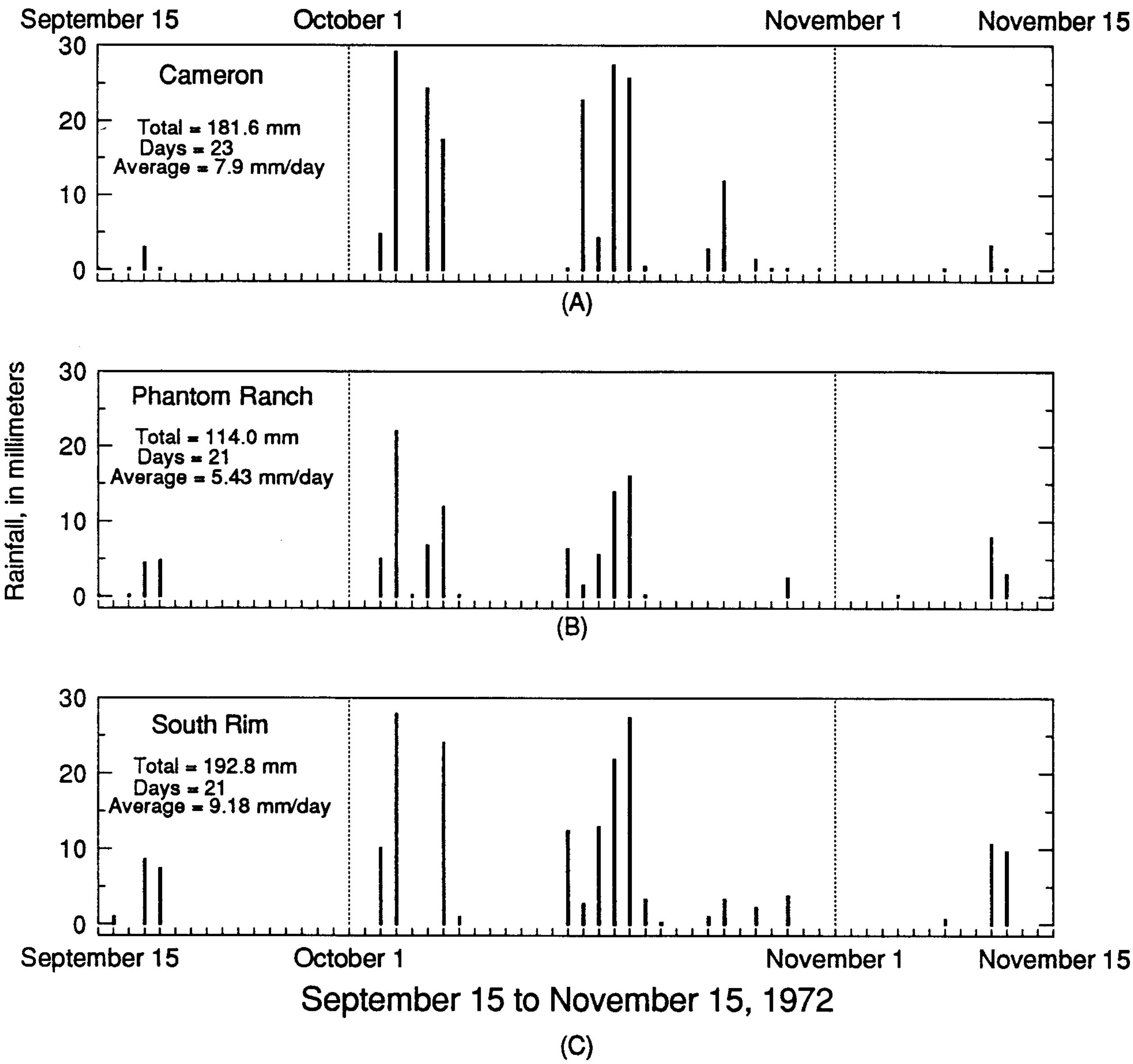



**Figure 17. Rainfall from September 15 to November 15, 1972, which includes the wettest October on record. (A) Cameron, (B) Phantom Ranch, and (C) South Rim.**

(Hereford and Webb, 1992). It is unlikely that widespread arroyo cutting occurred during the mid-1970s in eastern Grand Canyon.

Rainfall during the fall to winter season is illustrated in figures 20-22. Figure 20 shows the rainfall of fall to winter 1978-79, the wettest such season at the four weather stations (fig. 14). Rainfall greater than 20 mm occurred several times at each station between early November and mid-December. Winter 1978 was unusually wet throughout northern Arizona and flooding was widespread (Hereford, 1984). Although the effects of this rainfall in Grand Canyon are unknown, the arroyo cutting episode of the late 1970s to mid-1980s probably began with the fall to winter season of 1978-79, if not during the fall to winter season of 1977-78 (fig. 14).

Rainfall during early December 1966 caused floods and debris flows in eastern Grand Canyon, including development of Crystal Creek Rapids (Cooley and others, 1977). The documented effects of this storm include debris flows, extensive arroyo cutting in the

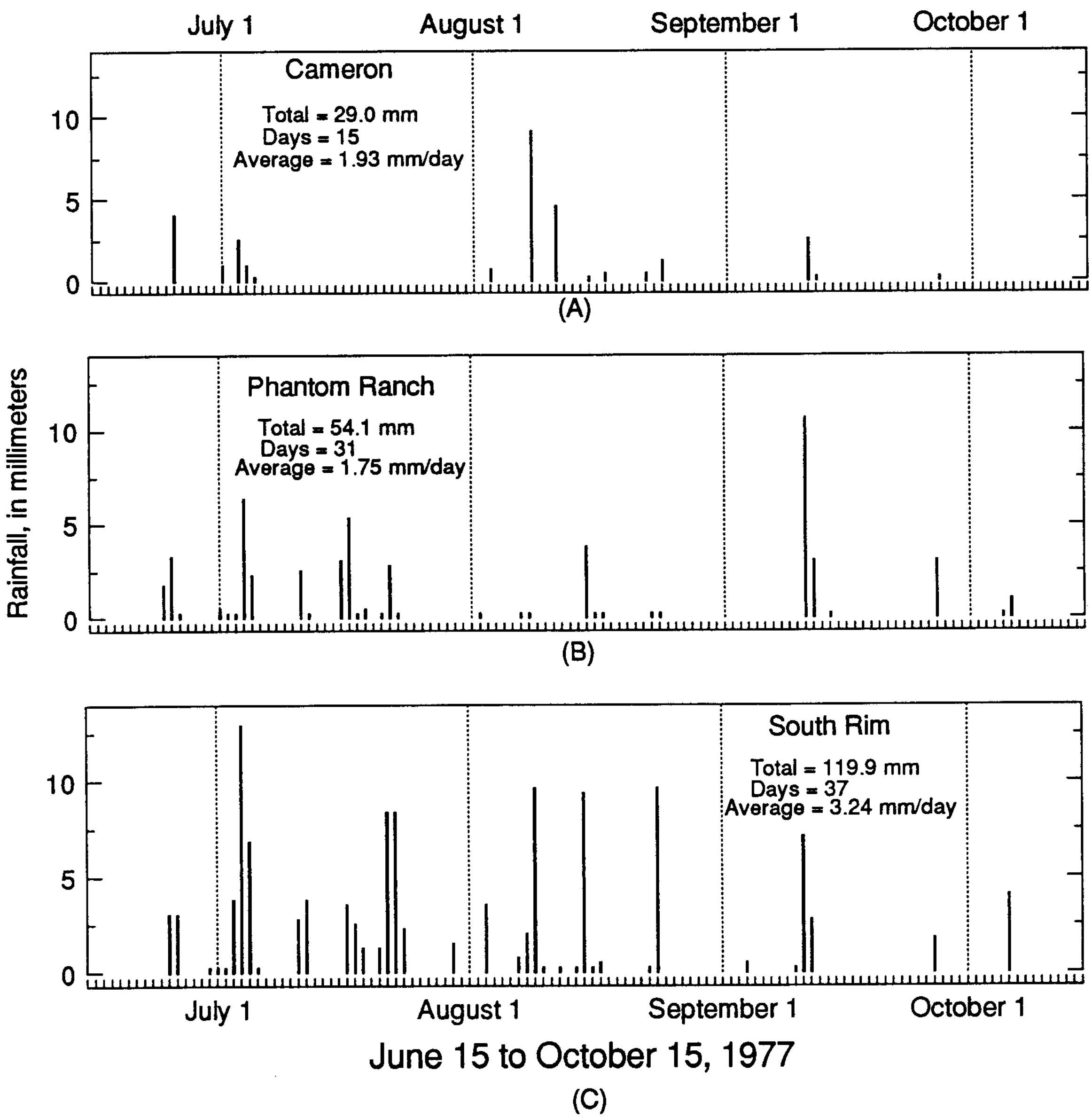



**Figure 18. Warm-season rainfall, 1977, a dry season. (A) Cameron, (B) Phantom Ranch, and (C) South Rim.**

large tributaries of the Colorado River with headwaters on the North Rim, and damage to archeologic sites. These sites had not been eroded since general abandonment of the Grand Canyon region by the Anasazi about A.D. 1150-1200; based on this, Cooley and others (1977, p. 42) concluded that the storm was a rare event in eastern Grand Canyon.

Figure 21 shows the occurrence of rainfall at three of the stations during December 1966. The storm was short lived, lasting only five days from December 3-7. Rainfall amounts were not particularly large at Phantom Ranch or South Rim, and rainfall at Cameron was negligible (fig. 21). Total December rainfall at Desert View was 110 mm (fig. 14), which is the second largest December rainfall on record. The storm was centered on the North Rim (Cooley and others, 1977, Plate 1), and rainfall amounts on the South Rim and the river corridor were large, but not excessive.

An unusually dry season, the fall and winter of 1988-89, is shown in figure 22. The daily rainfall pattern is similar to a wet season (fig.

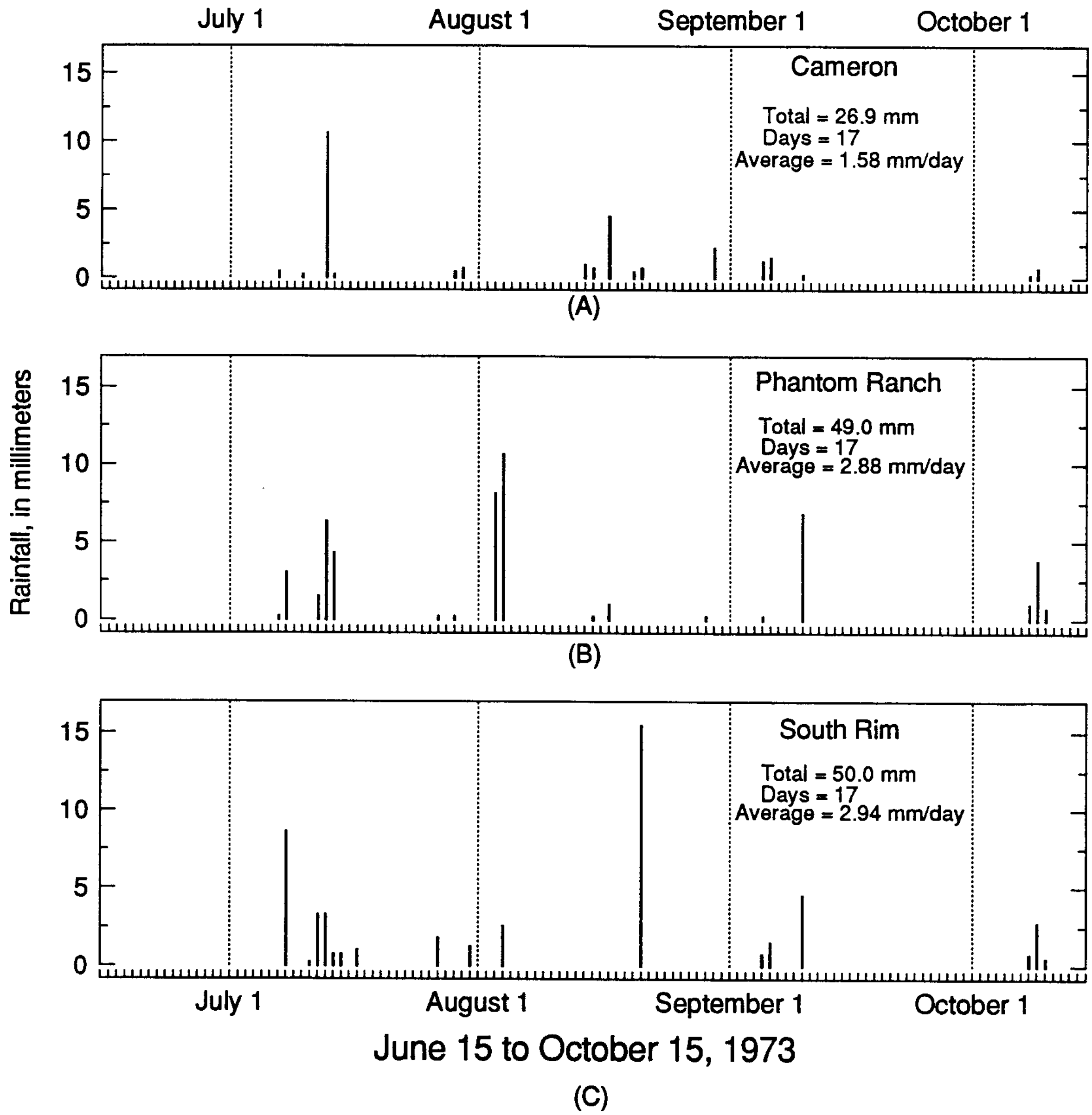



**Figure 19. Warm-season rainfall, 1973, a dry season. (A) Cameron, (B) Phantom Ranch, and (C) South Rim.**

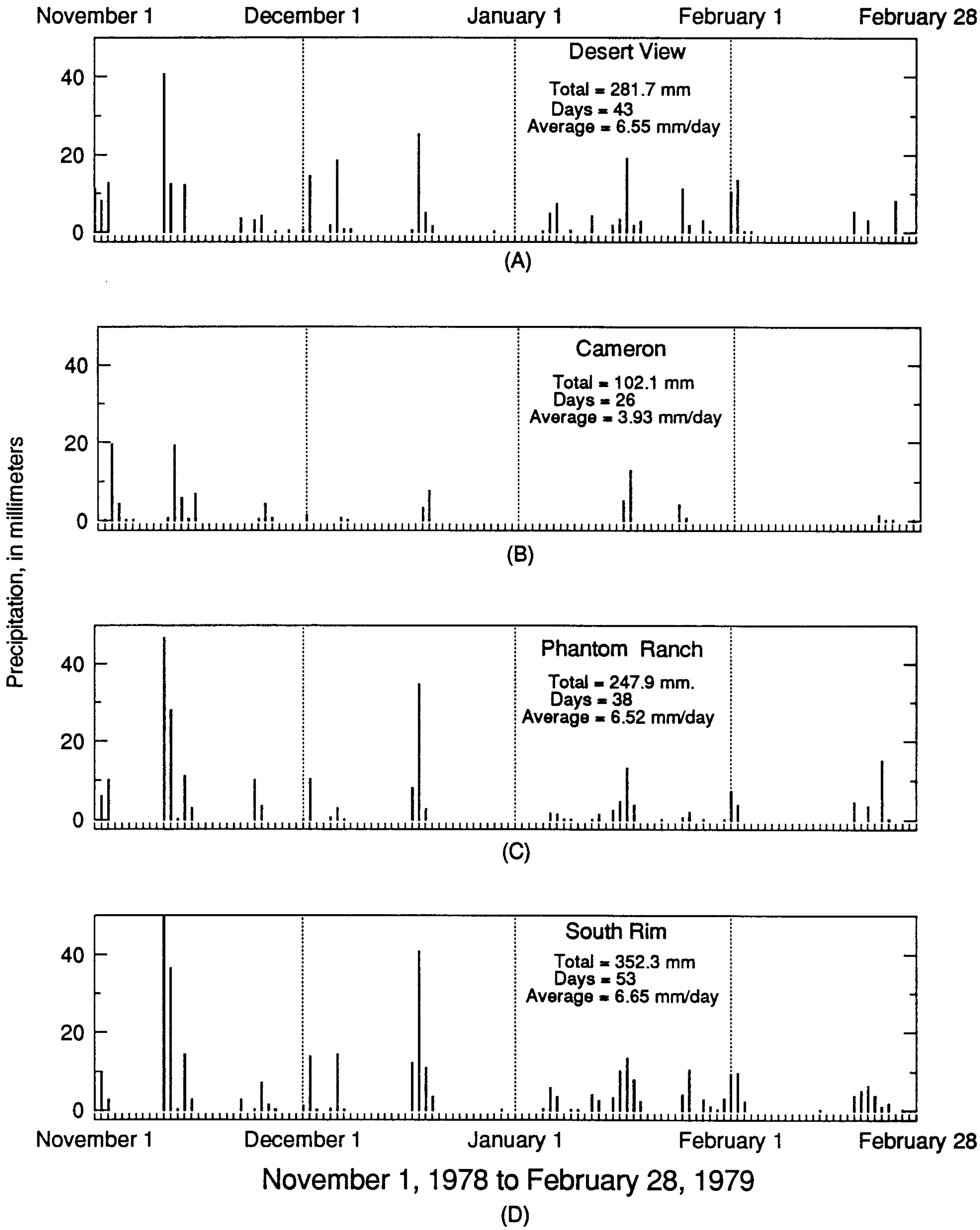



**Figure 20. Fall to winter precipitation, 1978-79, a wet season. (A) Desert View, (B) Cameron, (C) Phantom Ranch, and (D) South Rim.**

20), but daily accumulation and intensity are substantially less. Rainfall accumulation during a dry winter is about one-third the accumulation of a wet season, and rainfall intensity (mm $day^{-1}$ or daily total) is about one-half the intensity of a wet season. A rainfall pattern such as this would quite likely not produce significant runoff.

In short, runoff-producing rainfall in the eastern Grand Canyon region typically results from several multi-day episodes of high rainfall during the warm season or the late fall to winter season. The main indicator of significant runoff is the total amount of seasonal rainfall, which corresponds with relatively high rainfall intensity. Large rainfall events typically occur during the same stormy period or the same season, resulting in a broad synchroneity of fluvial activity in the region.

Total precipitation of the two seasons was analyzed for the period 1963-90. This analysis was undertaken to identify all seasons with

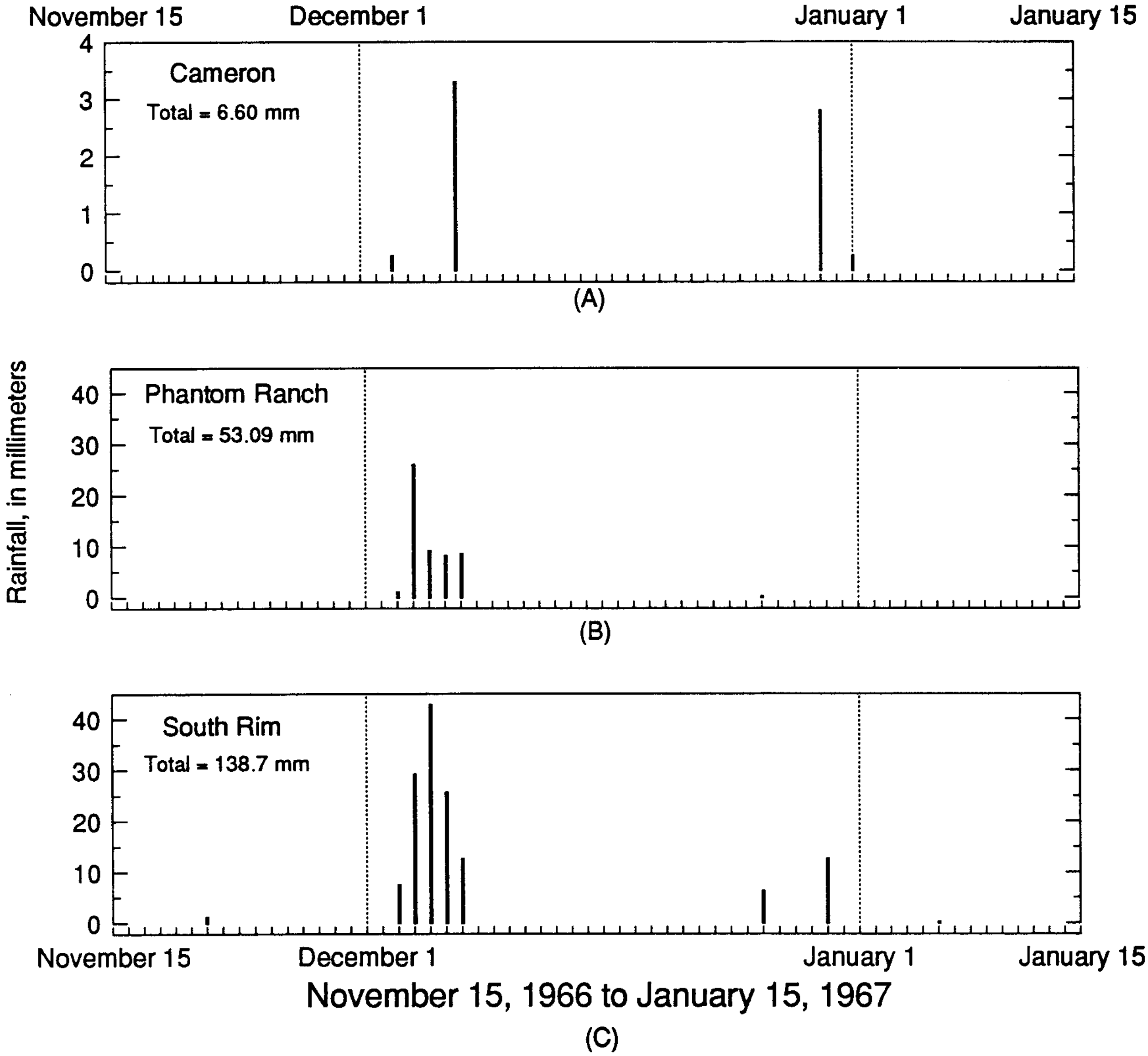



**Figure 21. Rainfall from November15, 1966 to January 15, 1967. Rainfall in December produced widespread runoff and debris-flow activity on the North Rim.**

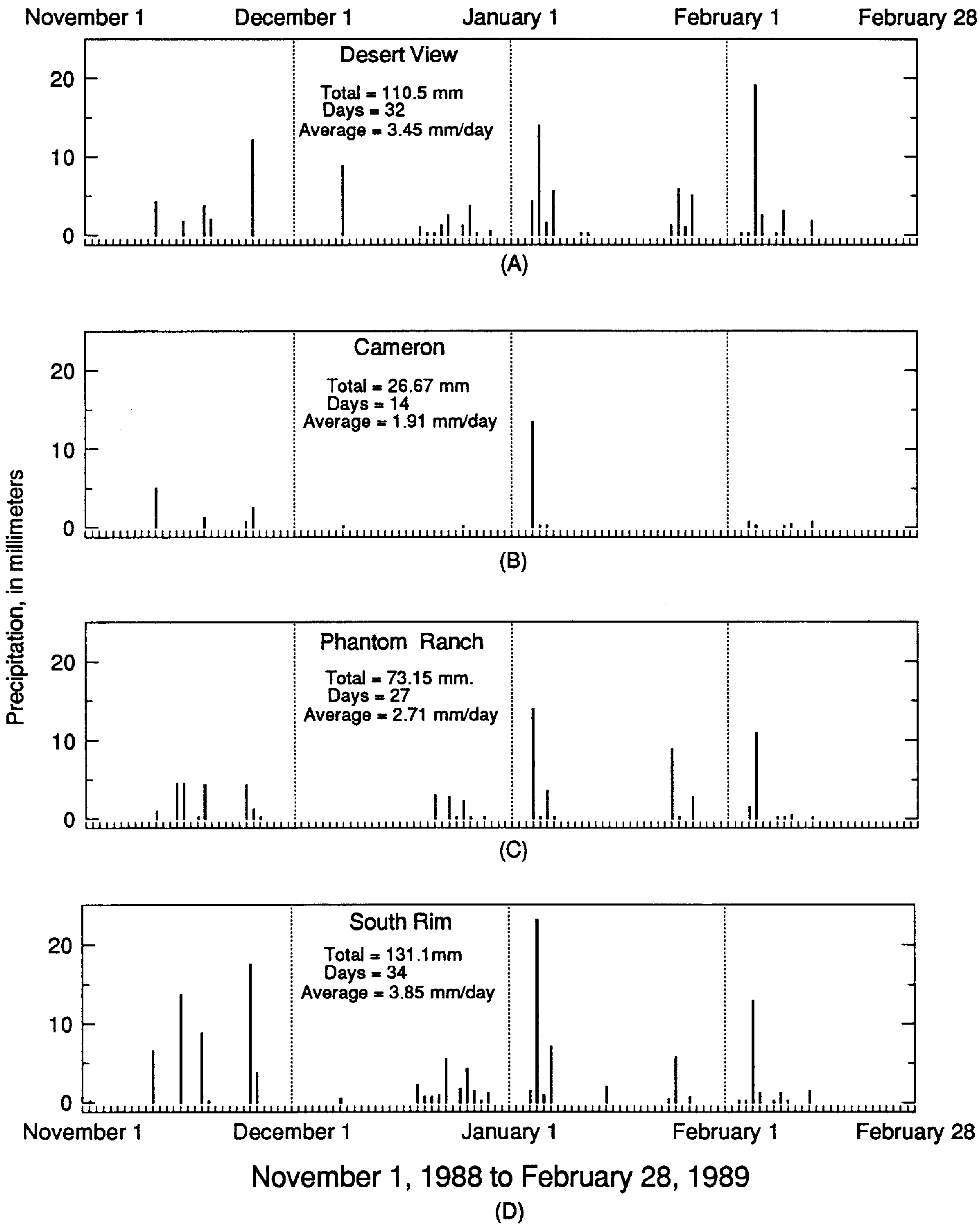



**Figure 22. Fall to winter precipitation 1988-89, a dry season. (A) Desert View, (B) Cameron, (C) Phantom Ranch, and (D) South Rim.**

sufficient rainfall to produce runoff. The results are shown in figure 23, which illustrates total rainfall of the warm season and fall to winter season. The latter season is assigned the year of the preceding warm season so that the precipitation is not split between years. The horizontal line is the total rainfall of the 1990 warm season of the particular station. As previously discussed, rainfall of this amount is known to be associated with runoff and debris-flow activity in eastern Grand Canyon. The amount of precipitation necessary to produce significant runoff is assumed to be about the same for each season. Using this assumption, total rainfall of the 1990 warm season was used to censor the data; any season having precipitation below this level probably did not produce enough runoff to cause arroyo cutting.

The correlation among the stations for a particular season is listed in table 4. The warm-season correlations are not significant in two cases; however, excluding Cameron, the Grand Canyon stations are reasonably well correlated with 67 to 76 percent variance reduction. Fall to winter season correlations are statistically significant and relatively high, ranging from 67 to 88 percent reduction in variance. This implies that total seasonal rainfall in the study area is predictable from the rainfall at the four stations.

Figure 23 shows that the warm season of 1963, 1966, 1967, 1972, 1981, 1983, and 1984 had rainfall equal to or greater than the 1990 seasonal total at 50 percent or more of the reporting stations, when two or more stations reported. Warm seasons with the largest rainfall were those of the early 1980s. Fall to winter precipitation was equal to or above the 1990 total at 50 percent or more of the reporting stations in 1965, 1966, 1977, 1978, 1982, and 1984 (fig. 23). Arroyo cutting was probably enhanced during consecutive seasons with unusual precipitation such as 1966 and 1984, as one wet season was followed by another, resulting in favorable antecedent moisture conditions.

The arroyo-cutting episode of the late 1970s to early 1980s indicated by photographic and field evidence (fig. 11) was caused by the unusual rain of fall to winter 1977-78 and 1978-79, warm season 1981, fall to winter 1982-83, warm season 1983 and 1984, and fall to winter 1984-85. In contrast, the apparent stability between 1985 to early 1990 is probably related to the lack of significant precipitation (fig. 23). The early period of stability from at least 1958 until 1973 (fig. 11) is more difficult to interpret. Precipitation was probably adequate in warm season 1963 and 1966, fall to winter 1965-66 and 1966-67, and warm season 1967 and 1972, but the photographic evidence shows no detectable change (fig. 11).

This apparent stability suggests that the sequence and size of events were not optimal. Six runoff-producing seasons occurred in 10 years (1963-72), which did not cause significant arroyo cutting. The arroyo cutting of the late 1970s to early 1980s, in contrast, probably resulted from the high frequency of unusually wet seasons and perhaps the cumulative effect of preceding events during 1963-72. This arroyo cutting was caused by seven wet seasons in only 8 years, from 1977-84.

**Table 4. Correlation matrix (Spearman correlation coefficient) of total seasonal precipitation at the four weather stations**

| Season | Cameron | Desert View | Phantom Ranch | South Rim |
|---|---|---|---|---|
| 6/15 to 10/15 | | | | |
| Cameron | 1 | | | |
| Desert View | 0.72 | 1 | | |
| Phantom Ranch | 0.54* | 0.82 | 1 | |
| South Rim | 0.43* | 0.79 | 0.87 | 1 |
| 11/1 to 2/28 | | | | |
| Cameron | 1 | | | |
| Desert View | 0.82 | 1 | | |
| Phantom Ranch | 0.83 | 0.89 | 1 | |
| South Rim | 0.89 | 0.88 | 0.94 | 1 |

* Correlation not significantly different from zero at the 0.05 level

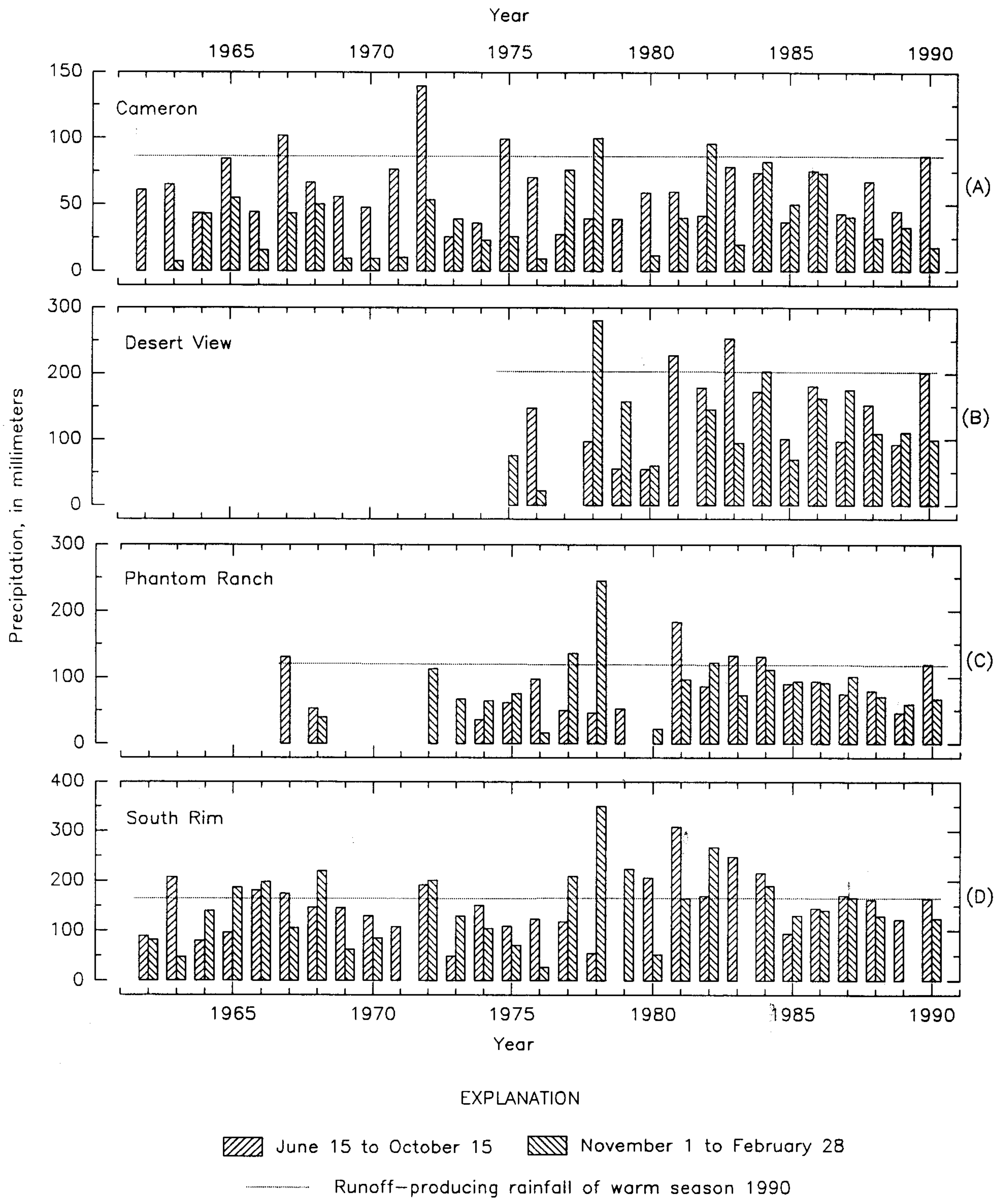



**Figure 23. Total seasonal precipitation at the four weather stations computed from the daily precipitation record. Horizontal line is the rainfall of 1990 warm season, which produced runoff and debris-flow activity in the study area. Missing data shown by a blank space at the year. Fall to winter season is assigned year of the preceding warm season. (A) Cameron, (B) Desert View, (C) Phantom Ranch, and (D) South Rim.**

## Discussion

The depth of arroyo cutting of streams draining small catchments in the river corridor is controlled largely by the depositional level of the Colorado River. This level was reduced by 3-4 m in the post-dam era, the result of reduced peak-flow rates and sediment loads. The extensive arroyo cutting from fall to winter 1977-78 through fall to winter 1984-85 resulted from an unusual run of wet years. This rainfall and the resulting runoff drove the erosional process, but baselevel controlled the depth of erosion, which is linked through the channel system to erosion throughout the catchment.

This implies that erosion leading to the present river-based streams might have been less in the pre-dam era under similar rainfall conditions, as explained below. Likewise, erosion in the future will be relatively high until the terrace-based streams reach and adjust to the new erosional level. This adjustment will occur through widening, deepening, and channel extension.

A river-based arroyo develops after a terrace-based stream reaches and flows over the edge of the pre-dam terrace. We hypothesize that the effects of flooding at the level of the pre-dam terrace prevented terrace-based streams from reaching the river, or at least slowed the rate of downstream channel extension. The pre-dam terrace forms a wide, nearly horizontal bench at the mouth of many arroyos, and the width of the terrace is a sizeable portion of channel length (fig. 12). Runoff debouching from the mouth of an arroyo loses velocity rapidly as it spreads unconfined over the porous, permeable sand of the essentially horizontal terrace. This reduced velocity causes deposition of a small alluvial fan on the terrace at the mouth of the arroyo, which retards arroyo cutting upstream. Coppice sand dunes typically cluster near the edge of the terrace; these mounds of sand cause runoff to pond, forming an additional barrier to channel extension. Eventually, deposition and build-up of the alluvial fan increases the channel gradient across the surface, and the stream will overtop the edge of the terrace in the low area between sand mounds. When this happens, a channel is established across the terrace, initiating a wave of arroyo cutting and basin expansion as the system adjusts to the new, lower baselevel. In the pre-dam era, this process was interrupted perhaps every 2 years, on average, when the river overtopped the terrace of the pre-dam alluvium during the June to early July snowmelt runoff. These floods removed any previously formed alluvial fans, filled incipient channels, and deposited sand and flood debris at the mouth of the streams, retarding channel extension.

## Conclusions

The largest concentration of archeologic sites in the river corridor occurs between River Miles 65-72, which is the study area in eastern Grand Canyon. The average number of sites in this 11-km reach exceeds 12 $km^{-1}$. The majority of the sites are of Anasazi cultural affinity, dating from the Pueblo I to Pueblo II period, or from about A.D. 800-1200, although Basketmaker II sites and protohistoric and historic age sites are also present. Recorded sites occur on or near the surface of a variety of late-Holocene deposits, although typically they are associated with two ancient, terrace-forming alluviums of the Colorado River. A substantial number of sites are also entirely covered by younger alluvial and eolian deposits, judging from sites exposed locally in the steep walls of small tributary streams. Thus, continued erosion in these streams has the potential to damage or remove more sites than are present on the surface.

Prehistoric archeologic sites are associated with two deposits that are largely of Colorado River origin. These deposits occupy a distinct topographic position in the river corridor that is identified by surficial geologic mapping. Specifically, they form the highest and most extensive terraces adjacent to the river (fig. 3). The deposits are referred to as the "striped" and "pueblo alluviums," respectively (fig. 2). These field terms reflect the red-gravel stripes typical of the former and the abundance of Pueblo II archeologic remains typical of the latter.

The deposits consist mainly of sand derived from the Colorado River and lesser amounts of interbedded gravel derived from the nearby bedrock hillslopes. Eolian sand is present locally in both units, but large sand dunes comparable to the presently active dunes have not been identified. These alluviums are closely associated spatially and temporally with large, ancient debris-flow deposits (fig. 2). The deposits constrict the width of the Colorado River channel. Downstream of the constrictions, recirculating flow developed in the river through a large range of discharges. In places, the pueblo and striped alluviums were deposited in these now abandoned, high-level recirculation zones.

The striped alluvium is dated radiometrically using $^{14}C$; the pueblo alluvium is dated radiometrically and by temporally diagnostic potsherds associated with the deposit (fig. 4). Radiocarbon dates from charcoal associated with hearths and lithic scatters beneath or on the surface of the striped alluvium suggest that deposition began sometime before about 400 B.C. and ended by about A.D. 300. These archeologic remains are among the oldest in the Grand Canyon. A period of erosion and nondeposition lasting about 300 years occurred before deposition of the pueblo alluvium, which began about A.D. 700 and lasted until A.D. 1150-1200. The relatively large thickness and aerial extent of the alluviums suggest that they represent two major aggradational episodes; something that has not been repeated on such a large scale.

The end of aggradation of the Pueblo alluvium was probably coincident with abandonment of the area by the Anasazi about A.D. 1200. After this time the striped and pueblo alluviums were eroded as the channel of the Colorado River shifted course. This erosional episode lasted from A.D. 1150-1200 until about A.D. 1400 (fig. 4). During this time substantial quantities of the striped and pueblo alluviums were removed along with unknown quantities of archeologic material. Moreover, this erosion exposed large areas of sand to eolian erosion, and most of the large coppice sand dunes are derived from erosion of these and younger alluvial deposits. This prehistoric erosion of archeologic sites is fundamentally different than the ongoing erosion of historic times, which occurs by the fluvial activity of short tributary streams that drain the river corridor.

Between about 1400 until the beginning of regulated flows in 1963, three terrace-forming alluviums were deposited. These deposits are comparatively thin and of limited areal extent; therefore, they probably do not represent significant aggradation. From oldest to youngest, they are referred to as the "upper mesquite terrace," "lower mesquite terrace," and the "pre-dam alluvium" (figs. 2-3). These occur in the old high water zone of previous studies. The deposits record the protohistoric to historic flood history of the Colorado River, including the flood of record in July 1884, estimated at 8,500 $m^3\ s^{-1}$ (300,000 $ft^3\ s^{-1}$). Several floods larger than the flood of 1884 resulted in deposition of the upper mesquite terrace. These terraces affect erosion of archeologic sites in the pueblo and striped alluvium, because the terraces are the erosional baselevel for most tributary streams. In addition, the terraces form a physical barrier between the river and the prehistoric deposits that protects them from direct erosion by the river.

Four deposits associated with regulated flows are present topographically below the pre-dam alluviums and topographically above the 140 $m^3\ s^{-1}$(5,000 $ft^3\ s^{-1}$) flow level. These are referred to as the "1983 flood sand," the "high-flow sand," the "fluctuating flow sand," and the "post-dam floodplain" (fig. 2). The first three occur as channel side bars or reattachment bars, and they resulted from the generally declining pattern of maximum releases since 1983. These deposits are typically moderately to well-sorted, very-fine to fine-grained sand that is less than 1 m thick. Their topographic position in the channel is significant to understanding erosion of archeologic sites, because they form a new and lower erosional level for tributary streams (fig. 13).

In prehistoric times, erosion of archeologic sites occurred during two episodes, each lasting several centuries. This erosion resulted from lateral migration and downcutting by the Colorado River. In contrast, during historic times, since about 1890, erosion of sites has occurred mainly by arroyo cutting in the short tributary streams that drain the terraces of the river corridor. This erosion was particularly intense during 1977-84 and less so in 1990-92. In eastern Grand Canyon, this recent erosion is largely unrelated to the daily operation of Glen Canyon Dam.

Active erosion of archeologic sites is documented photographically in parts of the study area (figs. 8-10). These photographs show that several archeologic features were destroyed between 1965-83. This erosion was first noted by Park Service archeologists. Initially, the high water of 1983-84 was thought to be directly responsible for the increased erosion.

Our investigations revealed that only one site was directly effected by the 1983 high water. In this regard, the eastern Grand Canyon is not typical of the entire river corridor. Indeed, about 7 percent of all recorded sites are within the 1983 flood zone and were directly effected by the 1983 flood and subsequent high flows.

Arroyo cutting increased in the post-dam era, coincident with the erosional damage of archeologic sites (fig. 11). Evidence of arroyo cutting is shown by sequential low-altitude aerial photographs (table 1), ground-based photographs (figs. 8-10), and field observations of ongoing erosion. Arroyos were generally stable from at least 1958 until late 1972-73. Arroyo cutting began in the area sometime between June 1973 and July 1978. This erosional episode lasted until fall to winter of 1984-85. After then until late 1989, aerial photographs show little change in the size and number of arroyos. This period of stability lasted until 1990, when erosion was observed again throughout the area. Erosion during the late 1970s to mid-1980s resulted in widening, deepening, and upstream and downstream extension of existing arroyos, as well as development of new arroyos. The present (1990-92) erosional episode appears to be a continuation of the earlier episode, although the effects are not as severe.

The tributary streams are ephemeral, and runoff occurs in direct response to rainfall in the river corridor. Significant rainfall occurs during the warm season, June 15-October 15, or the fall to winter season, November 1-February 28. Analysis of seasons known to produce runoff and debris-flow activity in eastern Grand Canyon shows that the main indicator of runoff is total rainfall, which corresponds with relatively high rainfall intensity (figs. 15-22). The period of arroyo cutting of the late 1970s to mid-1980s was the wettest of the post-dam era (fig. 23). During this time, seven wet seasons occurred in only 8 years. The early period of stability, in contrast, had six runoff producing seasons in 10 years from 1963-72. This frequency of runoff did not produce detectable arroyo cutting, although the cumulative effect of these events might have pre-conditioned channels for subsequent arroyo cutting.

Large-scale topographic maps (Plates 1-4) show that the short tributary streams have different baselevels, which are related to past and present depositional levels of the Colorado River. River-based streams drain to the Colorado River and have the lowest baselevel. Terrace-based streams do not reach the Colorado River; rather, their baselevel is above the river at the level of the pre-dam terraces. Generally, the channel of a terrace-based stream is free to extend downslope to the river, thereby becoming a river-based stream. In the pre-dam era, most tributary streams probably did not reach the river; they appear to have extended no farther than the pre-dam alluvium.

The difference in elevation between the pre- and post-dam depositional levels of the river is 3-4 m (table 2), the result of regulated flows. Thus, the potential depth of arroyo cutting of terrace-based streams has increased 3-4 m in the post-dam era. This increased depth of erosion implies that arroyo cutting will be intensified relative to conditions of the pre-dam era until the terrace-based streams adjust to the new, lower baselevel. In the short term, intensified arroyo cutting will probably effect terrace-based streams with catchment area larger than 3,000 $m^2$ whose channels end less than 100 m from the river (fig. 6). Perhaps 25 percent of all terrace-based catchments have these characteristics.

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